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Devoted to Science and the Mechanic Arts

Vol. 220 AUGUST, 1935 No. 2

THE THERMIONIC VALVE IN SCIENTIFIC RESEARCH.*

BY

SIR AMBROSE FLEMING, M.A., D.Sc., F.R.S.,

Emeritus Professor of Electrical Engineering in the University of London.
Franklin Medalist, 1935.

The Thermionic Valve, which as a technical invention has made possible the great achievements of telephonic broadcasting and television, arose out of scientific research intended to elucidate certain observed phenomena in connection with the working of incandescent electric lamps in 1882 and 1883. It has also provided in itself a new and valuable instrument of research for the physical investigator. The initial steps were taken in this invention when the writer as Scientific Adviser of the Original Edison Electric Light Company of London began to study the projection of carbon atoms from the carbon filament of the then used Edison carbonized bamboo filament electric lamps, which, together with the carbonized cotton thread incandescent lamps of Swan, provided the first practical domestic electric lighting system for general use. It was soon found that these lamps had a black deposit made on the interior of the glass bulb in course of

* Read by Dr. Howard McClenahan, Secretary and Director, at the Medal Meeting held Wednesday, May 15, 1933.

(Note—The Franklin Institute is not responsible for the statements and opinions advanced by contributors to the JOURNAL.)

time which was fairly uniform and was doubtless due to an evaporation of the carbon, which substance like iodine and camphor and some others passes from the solid state to the gaseous without any intermediate liquid state.

On the other hand in certain cases in which a line of no carbon deposit appeared on the bulb in the plane of the hairpin-shaped carbon filament, it was evident that the projection of carbon particles had taken place from one particular overheated point on the filament. This projection was due to a process of electric "spluttering" which was also the cause of a green copper deposit on the bulb in some cases, since in the Edison lamps the ends of the carbon filament were well connected to the platinum leading-in wires by an electrodeposit of copper over the clamp. This carbon sputtering then clearly took place along straight lines by reason of electric repulsion of carbon ions carrying an electric charge.

Edison had noticed in 1883, that when a metal plate carried on a wire was sealed through the bulb of his carbon filament lamp and connected externally to the lamp by a circuit joined to one or other terminal of the filament, an electric current flowed in this circuit if it terminated on the positive terminal of the lamp filament which was heated by a direct voltage but little or no current when the current terminated on the negative terminal of the filament. The author of this paper made an extensive investigation of the cause of this effect which Edison had not explained or utilized. This was published in 1896 in the *Proceedings of the Physical Society of London* and in the *Philosophical Magazine* for July 1896.

In this paper an extensive set of experiments was described which proved that certain particles charged with negative electricity were being ejected from the incandescent filament of carbon or from metal wires raised to incandescence in an evacuated bulb. It was at first assumed that these carriers were atoms or ions of carbon. It was proved that they were material particles of some kind, but it was not until four or five years later that Sir Joseph Thomson showed that they were the particles of ultra-atomic size we now call electrons.

Amongst the experiments described was one in which a grid formed the positively charged anode plate by which the electrons shot off from the filament were collected.

It was then proved in the above mentioned paper that if a highly evacuated glass bulb had in it one hot carbon and one cold metal electrode the space between had a unilateral electric conductivity and could convey negative electricity from the hot cathode to the cold anode but not in the opposite direction. A large variety of experiments supported this conclusion.

No additional uses or practical application of this fact was made until after the advent of electromagnetic wave telegraphy, when it became evident that it would be necessary to replace the capricious and easily disturbed coherer by some more certain device as a detector of the feeble high frequency electric currents or voltages induced in the receiving aerials of wireless telegraph apparatus.

The writer then made in November 1904 the type of rectifying electronic valve since associated with his name which converted these small alternating currents into direct currents which could be detected by galvanometers or telephone receivers and thus made signal-detecting instruments in this system of wireless telegraphy. It consisted of a carbon-filament vacuum lamp having a metal cylinder round the filament, the said cylinder being carried on a wire sealed through the wall of the glass bulb.

This Fleming rectifying valve came immediately into extensive use by Marconi's Wireless Telegraph Company in England as a practical wireless detector. It preceded by two years the invention of the first crystal rectifying detector of H. H. C. Dunwoody, namely the carborundum crystal detector patented in the United States in 1906, No. 837,616, or British patent No. 5332 of 1907.

It is frequently stated that the early Fleming Valves were merely low vacuum, or as we should now say, soft valves. This however is quite incorrect. In the writer's British Specification No. 24,850 of 1904 or U. S. A. Specification No. 803,684 of 1905 it is clearly stated that a high vacuum is to be made in the bulb and as a matter of fact some of the earliest valves made were exhausted by the use of the beautiful

process of Sir James Dewar in which the high vacuum is made by the absorptive power for gases of cocoanut charcoal cooled with liquid air.

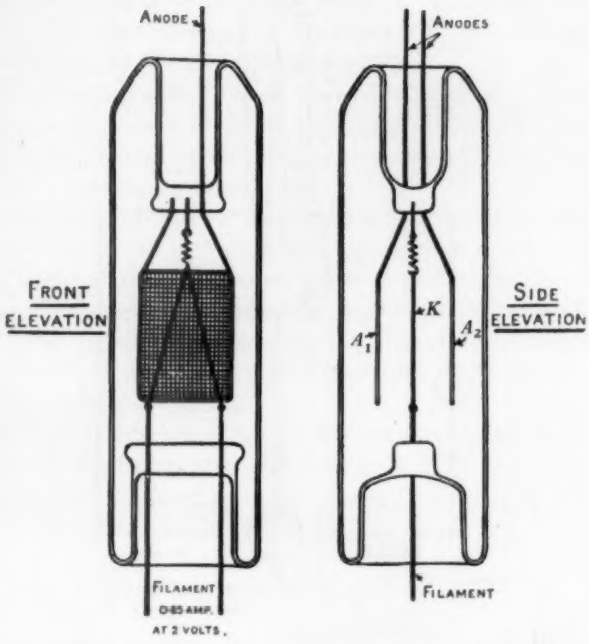
In this case the electric current in the valve is wholly conveyed by electrons emitted by the incandescent filament and not by ionisation of residual gas atoms in the bulb. It was not then a subsequent invention to create what is now called a "hard" valve. Some of the earliest experimental thermionic valves were quite hard. The writer also showed that by the use of two such rectifying valves both phases of an alternating current could be rectified or converted to direct currents. The addition of the "grid" between the "plate" or anode and the incandescent filament which converts the rectifying valve into an amplifying valve was first described by Lee de Forest in his British patent specification No. 1427 of 1908, dating however under the convention as from January 29, 1907.

But the strange thing is that this British patent for an important improvement was allowed to lapse in 1911, whereas it could have been maintained for fourteen years from the date of application in England by payment of fees. It would however be foreign to the purpose of this short paper to enter into any description of the many various important modifications of these two and three electrode thermionic valves for technical purposes in radio-working, as the immediate object here is to mention the applications of them in pure scientific research.

One of those made by the writer in 1931 comprised the use of a valve having a single hairpin-shaped filament of thoriated tungsten, commonly called a dull emitter filament, placed between two equal and equidistant grid wire anodes on either side. These grid anodes were of rectangular shape and formed of 18 vertical fine wires, and 27 horizontal wires interlaced so as to form a network anode of fine wires, the anode area being 9 centimetres square. Each anode was one centimetre distant from the filament. (See Fig. 1.) The filament was rendered scarcely incandescent by 2 volts, E.M.F. from a single cell accumulator.

The two grid anodes were connected with the filament through equal resistances with the two coils of a sensitive

FIG. 1.



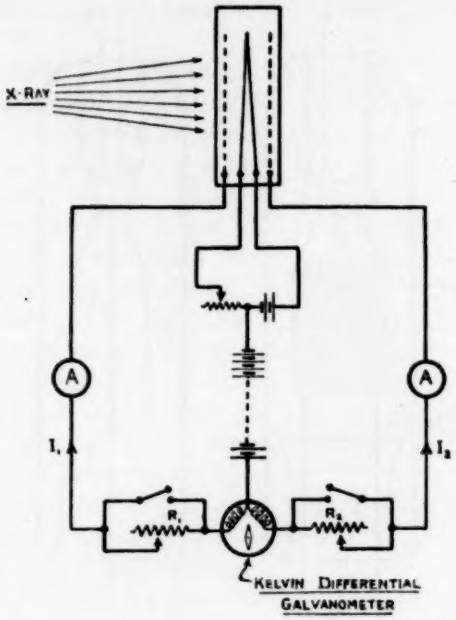
Special two-anode Fleming thermionic valve with dull-emitter filament.

differential galvanometer as shown in Fig. 2, and the common part of the circuit had in it a battery of 4 volts E.M.F. When adjustments of resistance on the two sides were carefully made the galvanometer needle remained at zero when the electron current flowing to each grid was 7·4 microamperes and the potential difference of the filament and each anode was close to 4 volts.

This arrangement proved to be a highly sensitive electroscope. If a stick of ebonite rubbed on the coat sleeve was held on one side of the valve on a line passing perpendicularly through the centre of the two grids, it caused the electrons on one side to be accelerated in their motion to the grid and on the other side to be retarded, and so caused a difference in the two currents and a large deflection of the needle of the differential galvanometer.

One experiment tried with this differential valve was to

FIG. 2.



Arrangement of circuits with two-anode valve for testing the effect of an X-ray beam upon a stream of electrons.

see whether a powerful beam of X-rays propagated with or against a stream of electrons could alter the velocity of that stream. It is well known that all optical phenomena can be divided into two classes. There are those like interference or diffraction which can be perfectly explained on a pure wave theory of light, assuming Maxwell's theory that the fluctuating variables are electric and magnetic forces or fluxes in the plane of the wave front and at right angles to the direction of propagation of it, these vectors being in phase with each other.

Then in contrast with this are phenomena such as the photoelectric effects which seem only explicable on the theory that light consists of photons or quanta of energy of magnitude $h\nu$, where h is the so-called Planck's Constant and ν is the frequency of that light. The difficulty however is to visualize a quantum of energy. On the other hand an electron

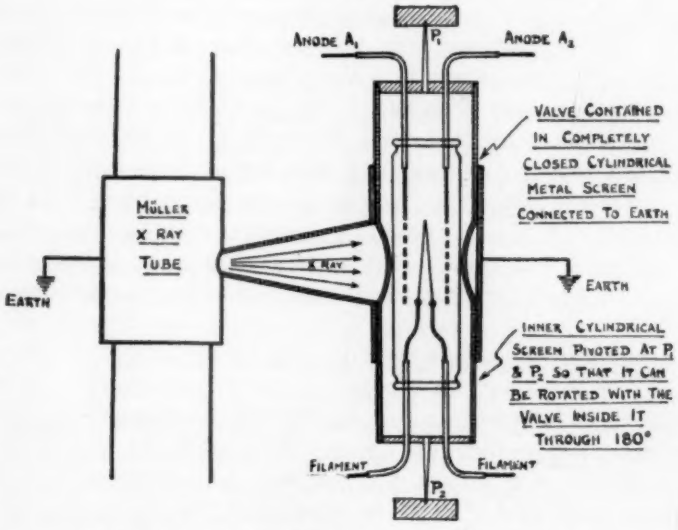
itself gives evidence of possessing a wave-like nature as shown by the experiments of Davison and Germer, described in 1927 and of G. P. Thomson in 1929.

The Compton effect made known in 1923 also proved that photons could rebound from electrons in atoms, the loss of momentum of the photon being represented by the momentum given to the recoiling electron.

If then the energy of light is concentrated in photons or packets each of energy ($h\nu$) and momentum $h\nu/c$, and if the wave-length of an electron of mass m and velocity v is given by h/mv it seemed an interesting experiment to ascertain if a powerful beam of X-rays containing therefore photons of high energy could alter the speed of electrons in a stream flowing with or against the photons.

The above described valve was used enclosed in a brass case with a hole opposite the grid (see Fig. 3). The X-rays

FIG. 3.


ANODE A1
P1
ANODE A2
VALVE CONTAINED IN COMPLETELY CLOSED CYLINDRICAL METAL SCREEN CONNECTED TO EARTH
MÜLLER X RAY TUBE
X RAY
EARTH
EARTH
INNER CYLINDRICAL SCREEN PIVOTED AT P1 & P2 SO THAT IT CAN BE ROTATED WITH THE VALVE INSIDE IT THROUGH 180°
FILAMENT
FILAMENT
P2

Two-anode thermionic valve with earthed metal screen round it.

were provided by a Müller structure X-ray tube with hot cathode actuated with 60,000 volts giving an electron current of 21 milliamperes striking the anode plate of the tube.

This is equivalent to 131×10^{15} electrons emitted per second. If each electron gave rise to a photon on striking the target and thus creating the X-ray beam and if each photon had an energy of 36×10^{-9} erg, since the frequency (which was not accurately measured) would be about 10,000 times that of visible light, the result would be that photons having a total energy of 524 million ergs would impinge on each centimetre square of the grid of the valve per second. On the other hand the electron current of the valve passing from filament to grid is 7.4 microamperes under an E.M.F. of 4 volts in power equal to 296 ergs per second or 33 ergs per centimetre square of the grid per second.

We have assumed as a limiting case that each electron in the X-ray tube striking the target produces one photon. If as a more probable value we take only 10 per cent. as so doing we had then two opposing streams, photons conveying 50 ergs per square centimetre per second and electrons opposing them conveying 33 ergs per square centimetre per second. The result of the experiment was that the incidence of this powerful X-ray beam produced not the smallest disturbance of the electron stream although a variation of 1 part in 2,000 of the electron currents in the valve could have been detected. It cannot be said that this result is inconsistent with the Compton effect because the two cases are different. In the Compton effect the X-rays are scattered by a solid body (? carbon) and the electrons from which the photons rebound are tethered in atoms. But in the case of my valve experiment the electrons are free and somewhat widely spaced apart.

A calculation shows that in 1 centimetre square of cross section of the electron stream to each grid there would be about 1,200 electrons, and in the X-ray beam about 600 photons passing through them. It would appear then that the chances of a collision of photon and electron are very small and all that the above experiment really proves *is* the exceedingly small space occupied by the electrons or photons out of the total volume occupied by any number of them in such streams as here employed. The question how the negative result above mentioned is to be interpreted is conditioned then by suppositions as to the actual nature of

photons and electrons for which we have little or no unquestioned facts. Even assuming that both are some kind of wave the photons can only move at the rate of 3×10^{10} centimetres per second and have no "rest mass." The electron can move at any speed less than 3×10^{10} centimetres per second and has a rest mass equal to its intrinsic energy divided by 9×10^{20}. If the electron is indeed a group of waves we have as yet no explanation why electron repels electron or how a photon can collide with it.

The experiment does suggest however some reconsideration of our ideas as to the nature of electrons and photons. When we speak of an electron as "particle" that immediately raises the question What is this particle made of? And even if we assume the existence of subelectrons we ask What are they made of? and so on. The same for photons often asserted to be the "particles" or "quanta" of energy.

The new quantum theory suggests to us that we must think of electrons as wave groups in a medium and that may involve that the so-called motion of an electron is not a bodily movement of something retaining a constant individuality but the cessation of some kind of wave in one place and its re-creation in another. The photon on the other hand may be regarded simply as a singularity on the wave front of the light, a locality where the amplitude of the light vectors is greater than the average, thus giving as Sir Joseph Thomson called it a "speckled" appearance to the wave front. As the wave passes over atoms it is only at these singularities that the energy is great enough to cause a possible elevation of an orbital electron to an orbit of greater potential energy. For visible light the energy of a photon is about 3×10^{-12} of an erg. For X-rays it may be about 10,000 times greater or of the order of 10^{-8} of an erg. The energy required to remove an electron from a metallic atom may vary from about 2.7 to 6.3 billionths of an erg ($= 6.3 \times 10^{-12}$ erg) and hence to raise it from one orbit to another will require rather less.

We must bear in mind however that the mental pictures we are able to form of physical events are in any case only symbols or hieroglyphics and may bear no more resemblance to the actual event or phenomenon than the written or

printed marks which form what we call a "word" bear to the form of the thing that word denotes.

Our mental pictures are made up necessarily of fragments of past sense impressions and the more easily or clearly we can build up a mental picture of a physical event the less is it likely to be true to fact. In any case it only suffices for a certain limited time and then has to be thrown on one side. Thus the Thomson mental picture of an atom was superseded by that of Bohr and that of Bohr by that of Schroedinger and that in turn by some yet unimagined conception.

We pass on then to mention some other interesting applications of the thermionic valve in scientific research and one of these is due to Dr. R. Whiddington, Cavendish Professor of Physics in the University of Leeds, described in the *Philosophical Magazine* of November 1920. If in a three electrode thermionic valve or triode, as it is often called, we couple inductively by a transformer the grid and the plate or anode circuits, and if the latter includes a capacity inductance closed circuit of low resistance then oscillations of frequency N are set up in this circuit determined by the capacity C and inductance L according to the law.

$$N = 1/2\pi\sqrt{CL}.$$

If the capacity C is provided by a parallel plate condenser the plates each having an area A and interdistance x then the frequency of the oscillations set up is given by

$$N = \sqrt{x/\pi LA}.$$

If a second valve oscillator is set up having a condenser of capacity C^1 which is adjustable, we can arrange that the frequency difference of the two sets of oscillations comes within the audible range and creates "beats." These can be amplified by a valve amplifier and made to actuate a loud speaking telephone so that the beats per minute can be easily counted. If then the capacity C is varied by altering the distance x even by a very minute amount there is a change of beat frequency which can be counted and by which the change in the interdistance x can be measured.

Professor Whiddington found that it was quite possible to

detect a change in x of two to four-thousandths of a millionth of an inch in the interdistance of the flat condenser plates. The plates were normally about one-thousandth of an inch apart.

This apparatus is therefore capable of detecting a movement of the condenser plates to or fro of about 1/1200 of a millionth of an inch which is far less than that of a Whitworth screw micrometer. It could also be used to detect exceedingly small changes in di-electric constant of certain highly insulating liquids.

This invention can be applied in the design of many different instruments as for instance in the construction of a microbalance where the tilt of the balance beam due to a weight is made to alter the distance between two condenser plates.

In a paper by Dr. Whiddington and Mr. F. A. Long in the *Philosophical Magazine* for January 1925, it was shown that it could be employed to estimate a change of weight of 10^9 gram in a load of about 0.2 gram. It would be applicable therefore to the measurement of the displacement of a torsion balance under very small forces such as the measurement of the gravitational constant of matter or the pressure of radiation.

Another very interesting application of the thermionic triode is in the production of electric oscillations of exact frequency controlled by a tuning fork, reed or phonic wheel. This application was originally due to Dr. W. H. Eccles and Mr. Jordan and described by them in a British Patent Specification by W. H. Eccles and F. W. Jordan, No. 155,851 of April 17, 1918 (see also W. H. Eccles, *Proc. Physical Society*, London, Vol. 31, p. 269, 1919). If it is desired to obtain electric oscillations or rather alternating currents of perfectly constant frequency within the limits of audition, it would in general require a very large capacity and inductance in the anode circuit of a thermionic valve with grid and plate circuits coupled as usual in the retroactive use of the valve for the production of such an alternating current. The frequency in any case is not entirely independent of the resistance of the circuits by heating. Hence it is difficult to preserve an absolute constancy in the fre-

quency. Yet for certain purposes in telephonic research on the calibration of electric-wave meters an absolute or high degree of constancy may be essential. Dr. Eccles' method for audio-frequency oscillations is as follows:

A steel tuning fork has two electromagnets placed in contiguity to its prongs. A triode valve has one electromagnet coil in its grid circuit and the other in its plate circuit and they operate in the following way. When the fork is started in vibration and one prong approaches the iron core of the electromagnet it creates in the coil an electromotive force which causes the grid to become either positively or negatively charged. This then causes an increase or decrease in the plate current and it attracts or repels the other prong of the fork. If the connections are made the right way this action tends to keep the fork in vibration and to increase the amplitude.

Now the fork has a perfectly definite rate of vibration assuming it is kept at a constant temperature and the fork therefore controls the rate of the valve oscillations. The oscillations in the plate circuit can be transferred by means of a coupling transformer to any other circuit and if need be can be amplified so as to give a perfectly constant frequency in any alternating current required for research purposes. In the above case the fork can give vibrations within the range of audition but in some cases electric vibrations are required of a much higher frequency called supersonic. These can be controlled by employing the longitudinal vibrations of a steel rod instead of a fork clamped in the centre.

In those cases in which a still higher frequency is required we can make use of the piezo-electric properties of a quartz crystal. Certain crystals, viz., tourmaline, rochelle-salt and quartz have the property that when compressed along a certain axis an electric polarity develops along another direction. Quartz occurs in hexagonal or six-sided prisms. The longitudinal or symmetric axis is called the optic or Z-axis. The three Y-axes which are normal to the Z-axis and to the faces of the prism are the electric axes and there are three X-axes. If a rectangular slice is cut perpendicular to a Y-axis and its face parallel to an X-axis then if such a slice is compressed in one direction it will exhibit electric

charges in a direction at right angles. In that direction the crystal can also be set in stationary mechanical vibrations and corresponding to these there will be electrical charges produced on the faces of the slice. If then such a slice of quartz is placed between metal plates but is free to expand and contract and if the condenser so formed is coupled in between the grid and plate circuit of a triode in the right direction a tuned electric circuit having capacity and inductance with high tension battery in series inserted in the external filament-to-plate circuit and the grid resistance to the filament, electric oscillations will be set up in the quartz plate and mechanical oscillations in the direction at right angles thereto. The rate of these oscillations is fixed by the dimensions and quality of the quartz plate, and its mechanical oscillations create the electrical, and the valve supplies the energy to maintain the electric and therefore the mechanical vibrations. These may be of frequency up to a million or more.

The crystal can be so cut that it has a high or low frequency rate of oscillation. The crystal controlled valve can then be used to keep perfectly constant the oscillations in a valve transmitter as used in wireless telegraphy.

Also the mechanical vibrations of the quartz generate supersonic air or sound waves, the properties of which have been carefully studied by G. W. Pierce and others.

The piezo-electric qualities of quartz plates cut in the proper direction from quartz crystals was investigated as far back as 1922 by Professor Cady in the United States, who described his researches to the Institute of Radio Engineers, U. S. A. Professor Pierce placed his work on record in the *Proceedings of the American Academy of Arts and Sciences* in 1923. Other exhaustive researches were made by D. W. Dye in 1923 and 1926 at the National Physical Laboratory, England, and other investigators have been G. W. N. Cobbold and A. E. Underdown in 1928 and J. E. P. Vigoureux in 1929 and by these investigators the action of a valve-maintained quartz oscillator has been carefully examined and described. A tuning-fork controlled thermionic valve is employed at the Rugby Wireless Station of the British Postal Telegraph Service to maintain constancy in the carrier wave frequency.

Other interesting applications of the thermionic valve in

research are in the construction of instruments for measuring small high frequency voltages, currents, and powers. The defect of all alternating current instruments depending on the heating power of the current is that as this heating varies as the square of the current the scale readings decrease more rapidly than the current.

Amongst such thermionic valve instruments may be mentioned the Moulin Voltmeter which enables the peak voltage and mean value of an alternating current of any wave-form to be measured by the same instrument. Mr. E. B. Moulin described this instrument in August 1928 in the *Journal of the Institution of Electrical Engineers*, Vol. 66, p. 886, 1928. It consists of a thermionic valve with filament heated by a 4-volt storage battery and the terminals to which the tested alternating voltage is applied connected to the grid and filament respectively of the valve, one through a high resistance shunted by a condenser for grid connection, and a direct reading microammeter for the filament connection. This instrument has the great virtue of absorbing little or no power. It is made in various forms by The Cambridge Instrument Company of England.

A very ingenious application of the three- or two-electrode valve has been made by Dr. H. E. M. Barlow in the construction of a valve ammeter for the measurement of small alternating currents of radio frequency. (See *Journal of the Institution of Electrical Engineers* of London for March 1925. Paper first received in February 1924.)

He constructs a Wheatstone's Bridge circuit two arms of which are formed of the interspace filament-to-grid or filament-to-plate of two thermionic valves. The other two arms are suitable resistances and a suitable microammeter is put in the bridge circuit and a high tension battery supplies current as usual to the circuits. A balance can then be obtained. The filaments of the valves are rendered incandescent by a suitable E.M.F. with a highly inductive coil in series. If then a small alternating current is superimposed on the direct filament heating current of one valve it upsets the bridge balance and causes a deflection of the microammeter.

It is then possible to calibrate the instrument so that the

readings of the bridge ammeter give the strength of the alternating current added to the direct heating current of one valve and such calibration is valid for all frequencies.

It is made to give full scale deflections for A.C. currents of 5, 10, 20, or 30 milliamperes. Dr. Barlow has also made a useful arrangement of two electrode valves for measuring very small condenser capacities.

A thermionic wattmeter has also been devised by Dr. E. Mallett in which two thermionic valves and a differential galvanometer are employed. But instruments of this type in which two valves of quite identical characteristics and a differential galvanometer are requisite are not very likely to come into any general use for commercial purposes.

The application shows however the extensive possibilities of the thermionic valve as an instrument for scientific research outside of and beyond its technical applications and general employment as an amplifier of voltage.

A New Wood-Waxing Process.—The U. S. Department of Agriculture has made public a method for increasing the permanency of wood developed by Dr. A. J. STAMM, chemist of the Forest Products Laboratory. The new process has definite advantages over the older methods which have been confined to direct impregnation of wax into the gross capillary structure of dry wood. Such processes, always incomplete, failed because when treated wood was exposed to moisture, the water quickly penetrated the millions of unsealed cavities and invisible openings in the wood tissue.

Dr. Stamm's process makes use of an intermediate or transfer solvent. Green wood whose natural water content keeps the submicroscopic membrane spaces wide open, can be used. "Cellosolve," a compound having the properties of both an ether and alcohol, is injected into the wood by a replacement process and acts as an intermediary substance. The water, because it boils at a lower temperature than does cellosolve, is distilled off.

Impregnated with cellosolve, the wood is next placed in a melted wax bath, and the replacement process is repeated, with the wax dissolving into and replacing the cellosolve which is in turn distilled off. Beeswax and stearin are two of the waxes successfully used in the process, but such substances as rosin and linseed oil can also be used with waxes in many combinations. With this new process, the green wood, when filled with waxes, very nearly retains its natural size even through wide changes in the moisture of the surrounding air. Loss of wood from checking, bowing, twisting, and the like therefore is largely eliminated.

C.

Cherries Versus Fish for Gulls.—CLARENCE COTTAM, food-habits expert of the U. S. Biological Survey, reports that gulls in the Salt Lake and Utah valleys of Utah have found a way to exploit the abundant cherry crops of the region. Although unable to alight in the branches with their webbed feet, these birds have learned to hover over the trees, beat the fruit down with their wings, then fly to the ground and help themselves. The birds have also been observed in the tops of the cherry trees, supporting themselves with outspread wings, and devouring all the fruit within reach.

C.

RADIATION REACTION FORCES AND THE EXPANDING UNIVERSE.

BY

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ABSTRACT.

The expanding universe is described in terms of the known forces of classical physics. It is shown that great clouds of stars are non-conservative systems and that radiation reaction forces play a part in guiding stellar motions. The forces are of importance in unsymmetrical stars and evidence is collected to show that perhaps all stars are possessed of deep seated thermal asymmetries. The forces continually act to increase the mean velocity of the stars and the galaxy is calculated to expand at a rate which closely approximates the observed rate of expansion. From a relation connecting the mean velocity of the stars and their age, it is deduced from the observed motions that the age of the galaxy is about 10^{10} years. The deduced rate of expansion of the galaxy agrees well with the observational data and is identical in form and numerical constant with Hubble's relation connecting the velocity of recession and distances of nebulæ.

Because of the relative size and spacing of the extra galactic nebulæ and the short time scale it is supposed that the nebulæ were formed by fission from a parent-super nebula and this resulted in thermal asymmetries which brought the newly considered forces into action. The resulting expansion was produced by slow evolutionary radiation processes which bear no direct relation to the properties of space or atomic constants.

The calculations suggest that in describing the motions of typical stars over long periods of time, radiation reaction forces are as important as the classical gravitational forces.

Statistical analyses of astronomical data relating to the motions of stars and nebulæ have revealed a number of definite relations between the masses, luminosities, positions, etc. of stars and their motions. These relations have not been given adequate physical interpretation, nor has it been possible to account for the presence in the universe of great numbers of visual binary star systems. The astronomers have long realized that purely gravitational forces were inadequate to describe all the observed motions of stars and in certain statistical analyses have found it necessary to introduce arbitrary constants into their equations. Campbell was the

first to notice that the mean radial velocity of the stars of our galaxy was definitely greater than zero and that the B type stars were receding with the greatest velocity. Slipher, and later Hubble, extended the observational data to nebulæ and found that these, too, are receding from us and at a rate proportional to their distance. If the usual interpretation of these data is accepted, it must be concluded that our universe is in unstable equilibrium and is expanding.

The present paper examines the effects of a non-gravitational force which continually acts on certain types of stars in such a way as to accelerate them and increase their kinetic energy. Such a continuing increase in kinetic energy, as will be shown below, causes the galaxy and the universe to expand at a finite rate. Other astrophysical effects of such forces have been previously pointed out by the author.[1] Therein it was shown that a definite thermal asymmetry in the radiating layers will cause more mass and momentum to be radiated from one hemisphere of a star than from the opposite one and that this loss of momentum to free space produces a reacting force on the star and increases its momentum by an amount nearly equal to the asymmetrical component of the radiated momentum. Thus a star gains kinetic energy and momentum in a manner not unlike that gained by a skyrocket. It will be convenient to establish the importance of the forces acting on the stars in our own galaxy by comparing the theory with observational data of a reliable nature and then extrapolate the results and apply them to the nebulæ.

THERMAL ASYMMETRY.

Observational data show that, statistically, every star probably becomes a nova once in about 10^9 years, or alternately, nearly every star has passed through the nova stage. It has often been suggested that the appearance of a nova is evidence of a rotational break-up of a star which, after passing through the planetary nebula stage, presumably evolves into one of the great number of observed binary star systems. Nova Pictoris (1925) is probably a good example of the early stages of such an evolution. Three years after its initial appearance as a nova it definitely developed into a multiple

[1] R. Gunn, *Phys. Rev.*, **39**, 130 (1932); *Phys. Rev.*, **43**, 764 (1933).

star system [2] and two of its components are now estimated to be receding from each other with a velocity approximately 250 times their parabolic velocity.[3] It is self evident that the stellar masses which resulted from the break-up of the parent star could not possibly have had a uniform surface temperature and hence radiation recoil effects might be expected to be large. Certainly, the present observed relative velocity of the two components indicate that gravitational forces are quite insignificant compared to the other forces acting. Moreover, reasonable assumptions regarding their surface temperatures lead to the conclusion that radiation reaction effects will adequately describe the present observed motions. These effects were considered in the reference cited and it was shown that the break-up of a star and the consequent radiation reaction forces would account for any type of observed binary system, provided the temperature of the hot face of the star approximated 10^7 degrees for a few hours, or, if the asymmetry persisted for some time, much lower temperatures would suffice.

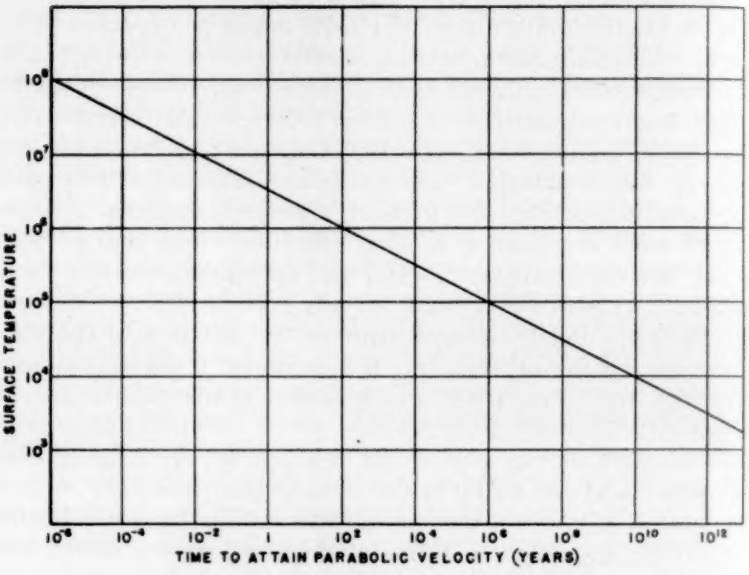
The curve of Fig. 1 gives the relation between the time it will take radiation reaction forces to impart parabolic velocities to two stars of the sun's mass and radius that are initially in contact, expressed in terms of the temperature of the hot face, always provided that the fourth power of the ratio of the temperatures of the cool and hot faces is small compared to unity. It appears significant that the time interval for stars of quite ordinary temperatures are considerably less than the indicated age of the galaxy.

It has been noted [2] that the difference in potential energy between a visual binary configuration and the same stellar components separated to infinity is very small compared to the total energy so that one may expect to find many single stars in the heavens which have experienced the fission process. We have reviewed the evidence for believing that the sun has divided as a result of rotational instability and shown how such a cataclysm could have produced the solar system.[4] The splitting of the sun necessarily left in its wake deep seated

[2] Finsen, MN, **88**, 488 (1928); **92**, 19 (1931).
[3] H. Spencer Jones, *Annals of Cape Observatory*, **10**, 177 (1931).
[4] R. Gunn, *Jour. Frank. Insl.*, **213**, 639 (1932); *Phys. Rev.*, **39**, 311 (1932).

thermal asymmetries and we interpret the very marked observed asymmetry of the sun's magnetic field as direct evidence of such a past cataclysmic disturbance.

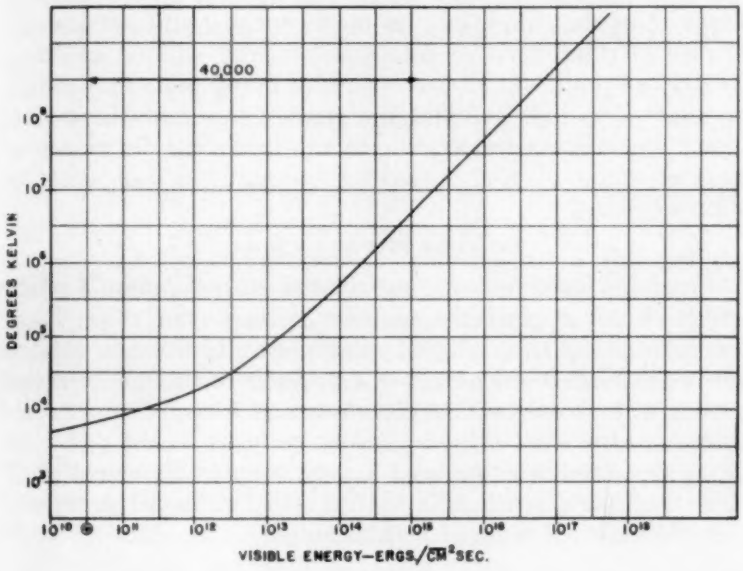
FIG. 1.



In order to estimate from observational data whether a nova might in fact be a star in the act of splitting, the rate of emission of energy per unit area by a black body has been calculated and the visible component of this energy between λ4,000 and λ7,600 plotted in Fig. 2 as a function of the black body temperature. If we suppose that a nova radiates like a black body and that the area of the primary emitting region is not changed by the break-up even though the ultimate radiating surfaces may be a greatly distended atmosphere. then one can estimate its effective radiating temperature from the observed fact that the apparent increase in luminosity of Nova Pictoris (1925), for example, was 11.5 magnitudes or a luminosity ratio of 40,000. This increase in the visible energy evidently corresponds to a far larger increase in the total energy of radiation and reference to Fig. 2 shows that if the star before break-up had a surface temperature of 6,000° its

effective temperature at maximum must have been nearly 10^7 degrees, whereas if it were initially at a temperature, 20,000° say (corresponding to a B type star, some of which are known to approach the condition of rotational instability), then the

FIG. 2.



maximum effective temperature must have exceeded 10^8 degrees. The assumptions of a constant primary area and black body radiation are, of course, open to some question, but these approximations could hardly alter the order of magnitude of the results. It is interesting to note further that the temperatures estimated agree quite well with the estimated internal temperatures of the selected star. If such stars did actually break up as a result of rotational instability, one hemisphere will necessarily be much hotter than the other and the radiation from it over a period of time will far exceed that from the cooler hemisphere.

These facts in addition to the large observed fraction of stars known to be double; the observed very rapid axial rotation of certain classes of stars; the definite asymmetry of the sun as exhibited by the non-uniform distribution of its

magnetic field; and other subsidiary evidence all indicate that the division of a star as the results of rotational instability is very common. Such a break-up of a star will result in the asymmetrical radiation of an appreciable fraction of its mass and will necessarily leave in its wake a marked and deep seated asymmetry. Not only will one side of a star be hotter than the other, but its mean density and presumably its rate of conversion of subatomic energy will be modified. Finally, we point out that the form of many planetary nebula are such as to indicate that the central star must have deep seated thermal asymmetries. In the following discussion we consider some of the important consequences of such inhomogeneities.

RADIATION REACTION FORCES.

Consider for simplicity an isolated star of mass M whose surface is at a perfectly uniform temperature T_0. Page[5] has shown that the radiated mass elements leave a uniform star with such momenta that an observer in any reference system will witness no acceleration and hence the net force acting on the star is zero. Now suppose a hot (or cold) region develops in some area having a mean temperature T. This thermal disturbance changes the radiated energy E from the selected region by an amount

$$\frac{dE_a}{dt} = f\sigma A(T^4 - T_0^4) = c^2\frac{dM_a}{dt},$$

where c is the velocity of light, f is a numerical factor somewhat less than unity whose value depends on the mean direction of emission of the mass particles with respect to the axis of thermal symmetry, σ is the constant in Stefan's law, A the effective radiation area of the spot and the subscripts denote that the asymmetrical component is to be employed. It is clear that a cool zone results in a force opposite in direction to that produced by a hot zone.

Let ΔM_a be the component of the radiated mass resulting from some asymmetry; then the momentum radiated along the axis of thermal symmetry is $fc\Delta M_a$. This lost momentum transfers a reacting impulse $\int Fdt$ to the star and it gains an

[5] Page, L., *Phys. Rev.*, 11, 377 (1918).

equal momentum. The fundamental relations are [1]

$$\frac{\Delta M_a}{M} = -\frac{\Delta V}{c} = \int \frac{F dt}{Mfc}, \tag{1}$$

where ΔV is the change in velocity of a star of mass M due to the lost momentum $fc\Delta M_a$. A more convenient form of Eq. (1) is

$$-\frac{1}{M}\frac{dM_a}{dt} = -\frac{b}{M}\frac{dM}{dt} = \frac{a}{fc}, \tag{2}$$

where a is the recoil acceleration and b is a characteristic constant for a given star defined by $\Delta M_a = b\Delta M$. Hence b is the ratio of the unsymmetrical component of the radiated mass to the total mass radiated in any selected interval.

Consider now the motions imposed on an isolated star rotating about its Z axis with an angular velocity ω. Suppose that a hot spot develops at a point on its surface whose co-latitude is θ and longitude measured from the Y axis is $(\omega t + \varphi)$; where φ is an arbitrary angle which specifies the longitude of the spot when $t = 0$. Suppose further that the reaction force is of the form $F = F_0 \exp(-\alpha t)$, where α is a decay constant and is supposed to depend only on the physical properties of the hot zone and t is the time measured from the time of break-up. The solution of the equations of motion show that the star describes a cycloidal-like path whose velocity components are

$$\begin{aligned}
V_x &= u_0 + \frac{F_0 \sin\theta}{M(\alpha^2+\omega^2)}\left[\alpha\sin\varphi + \omega\cos\varphi\right. \\
&\qquad \left. - \epsilon^{-\alpha t}(\alpha\sin(\omega t+\varphi) + \omega\cos(\omega t+\varphi))\right], \\
V_y &= v_0 + \frac{F_0 \sin\theta}{M(\alpha^2+\omega^2)}\left[\alpha\cos\varphi - \omega\sin\varphi\right. \\
&\qquad \left. + \epsilon^{-\alpha t}(\omega\sin(\omega t+\varphi) - \alpha\cos(\omega t+\varphi))\right], \\
V_z &= w_0 - \frac{F_0}{\alpha M}\cos\theta(1-\epsilon^{-\alpha t}),
\end{aligned} \tag{3}$$

and thus the final kinetic energy of the star after it has made many revolutions and the thermal symmetry has been nearly

equalized becomes by aid of Eq. (1) approximately,

$$W = W_0 + \frac{fcb\overline{\Delta M}\sin\theta}{\left(1 + \frac{\omega^2}{\alpha^2}\right)\alpha}\left[u_0(\alpha\sin\varphi + \omega\cos\varphi) + v_0(\alpha\cos\varphi - \omega\sin\varphi)\right] + \frac{f^2c^2b^2\overline{\Delta M^2}\sin^2\theta}{2M\left(1 + \frac{\omega^2}{\alpha^2}\right)} + w_0fcb\overline{\Delta M}\cos\theta + \frac{f^2c^2b^2\overline{\Delta M^2}\cos^2\theta}{2M}. \quad (4)$$

It will be noted that the last two terms refer to the polar asymmetries and do not depend on the stars rotation or upon α. It is presumed that the initial velocities of the stars will be distributed at random and that hot zones can be centered at any latitude; therefore, in considering great aggregates of stars, only the first, third and fifth terms of Eq. (4) are important. The importance of the third term depends critically upon the relative rates of rotation of the star and the rate of decay of the radiation stimulated by its break-up. Thus if $\omega < \alpha$ the added kinetic energy due to this term, is considerable. Most light curves of novæ decrease several magnitudes within a period of 2 or 3 weeks and this is comparable to the rotational period of known stars so that the required condition is at least approximately satisfied. Therefore, the third and fifth terms statistically contribute about equally to the increase in kinetic energy. Thus, since hot zones resulting from fission may be supposed to develop at any co-latitude, it is convenient to insert an average value $1/2$ for the trigonometric term; henceforth, limiting the discussion to statistical values. Passing therefore from the case of a single star to the consideration of an average star in a great cloud, Eq. (4) may be written in the convenient form

$$W = W_0 + \frac{Mf^2c^2b^2}{4}\left(\frac{1}{M}\frac{dM}{dt}\right)^2 t^2, \quad (5)$$

where $(1/M)(dM/dt)$ is taken to be the mean value of the quantity over the time interval t. It is supposed that almost all stars have experienced the fission process and that these

cataclysms left one-half of the star much hotter than the other.

By Poincare's theorem the internal thermal energy of a star of uniform density and radius R is given approximately by

$$W_2 = \frac{3}{4}\frac{\gamma M^2}{R}. \tag{6}$$

where γ is the gravitational constant.

Conduction and radiation processes strive to equalize the temperature and it is proper to suppose that the internal flow of energy approximates the radial outward flow of radiant energy. Now the outward flux of energy or luminosity of a star is given by the well-known empirical relation $L = \beta M^3$ where $\beta = 4.7 \times 10^{-68}$ so that the relaxation period necessary for the star to equalize its temperature is given as regards order of magnitude, at least by

$$\tau = \frac{3\gamma}{4\beta RM} \tag{7}$$

and τ for a star like the sun approximates 3×10^8 years. Thus radiation reaction forces due to a single break-up of a typical star with a polar type asymmetry continue to add energy to it for a period comparable to its life. Further, it must be noted that we have neglected the effects of subatomic transformation of energy and these certainly would prolong and accentuate the effects of an initial deep seated thermal symmetry. Therefore, we feel justified in assuming that the above radiation processes are more or less continuous when applied to a statistical treatment of great aggregates of stars.

If great numbers of stars are considered in all states of evolution it is clear that the process of fission will result in a statistical increase in the kinetic energy of the system. A discontinuity is to be expected in the kinetic energy of a star that has just split up [1] and one should expect subsequently a slow but more or less regular increase in its velocity or kinetic energy. There are observational data which bear out these inferences and we now turn to their consideration.

TABLE I.
Main Series Stars.

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
Type.	Temp. $\times 10^{-3}$ degrees.	Mass $\times 10^{-33}$ grams.	Lum. $\times 10^{-33}$ erg.-sec.$^{-1}$.	$\frac{1}{M}\frac{dM}{dt}$ $\times 10^{20}$.	$\sqrt{\overline{V^2}}$ $\times 10^{-5}$ cm. sec.$^{-1}$.	$W \times 10^{-26}$ gm. cm.^{2} sec.$^{-2}$.	$\frac{\sqrt{\overline{V^2}}}{C}$ $\times 10^5$.	$\frac{\Delta V}{C}$ $\times 10^5$.	$\frac{\frac{\Delta V}{C}}{\frac{1}{M}\frac{dM}{dt}}$ $\times 10^{-15}$ sec.	$\frac{\frac{\Delta V}{C}}{\frac{1}{M}\frac{dM}{dt}}$ $\times 10^{-8}$ years.	$\Delta\tau$ $\times 10^{-8}$ years.
B_0	23	17.8	1436	8.9	*14.8*	*3.9*	*4.94*	0.35	0.57	0.18	1.32
B_5	15	12.9	396	3.41	*15.8*	*3.24*	*5.25*	2.9	Fission-Unstable		
A_0	11	12.1	173	1.59	24.5	7.53	8.2	1.78	1.3	.41	3.0
A_5	8.6	8.0	82.7	1.15	29.9	7.12	10.0	2.0	2.05	.65	4.8
F_0	7.4	5.0	35.8	.796	35.9	6.48	11.95	3.97	5.88	1.86	13.6
F_5	6.5	3.1	15.5	.556	47.8	7.10	15.9	5.6	12.6	4.0	29.0
G_0	6.0	2.0	5.98	.332	64.6	8.34	21.9	4.36	16.2	5.18	38
G_5	5.6	1.51	2.74	.204	77.7	9.36	25.9	.568	3.5	1.1	8.1
K_0	5.1	1.35	1.49	.118	79.4	8.52	26.5				
K_5	4.4	1.23	.48	.043	74.2	6.77	24.7				
Ma	3.4	1.18	.04	.004	77.7	7.32	25.9				
Nebulæ		5.2×10^5	6×10^5	.0128					Total		97.8

A VELOCITY-AGE RELATIONSHIP.

Adams, Stromberg and Joy, and also Sears,[6] all of the Mount Wilson Observatory, have carried through important statistical analyses of the mean energies of the stars of our galaxy and emphasized the apparent equipartition of the kinetic energies. Sears points out clearly enough that equipartition could hardly be expected because of the relative improbability of astronomical collisions between stars. In this paper, Sears' data are interpreted in quite a different manner and are used to determine the apparent age of the galaxy.

We have brought together in Table I much of Sears' observational material and pertinent data derived therefrom. The most significant facts brought out by the data are the apparent increase in velocity of the stars with advancing spectral type and the discontinuity in velocity between the B and A type stars (column VI). One certainly should not expect from a priori considerations any systematic trend, yet the data show a definite and regular increase in mean velocity from the early B type to the late K type stars. Further, if binary star systems are actually formed by fission, we have noted [1] that a discontinuity in velocity might be expected just where Sears found one, because the only stars which appear to rotate very rapidly on their axes are B type stars and are, therefore, the ones most liable to break up.

Now, there are data which indicate that, statistically at least, the late type stars are actually older than the early type stars and, therefore, it is supposed that in the earlier stages of evolution of our own galaxy the stars were born with relatively small mass, while those generated later possessed progressively greater and greater mass. It seems fairly certain from the general results of this paper that no star which is now visible could have radiated away more than 1 per cent. of its mass; thus evolution from type to type by means of mass radiation is impossible and it is here properly supposed that a star is born to its position in the mass luminosity curve.

Solving Eq. (5) for the mean change in velocity $\overline{\Delta V}$ of a

[6] Sears, *Astrophys. Jour.*, **55**, 165 (1922). Adams, Stromberg and Joy, *Astrophys. Jour.*, **54**, 9 (1921).

typical star due to radiation reaction forces in the time interval τ one finds

$$\tau = \frac{2^{1/2}\overline{\Delta V}}{fbc\left(\frac{1}{M}\frac{dM}{dt}\right)} = J\overline{\Delta V}, \tag{8}$$

where, as before, one deals with mean values. The mean ages of the various types of stars are not well known, but by aid of Eq. (8) which assumes that the increase in velocity is due to the unsymmetrical radiation of mass and Sears' data, the mean difference in age of stars of different classes or masses can be estimated. The results of these calculations are summarized in Columns XI and XII of Table I. The total age of any star probably does not exceed twice the sum of the intervals listed or about 2×10^{10} years.

It has been assumed in the calculations that radiation from a given zone was emitted through a hemisphere and therefore $f = 0.64$. The factor of asymmetry, b, is not so readily determined. Immediately after fission practically the entire radiation is from one face and b is nearly unity, but as time goes on, the temperature distribution becomes equalized so that b becomes very small. However, even when one surface hemisphere is 10 per cent. hotter than the other, b still approximates 0.2. Rough calculations suggest that a mean value of b over the entire period of evolution approximates 0.3 and we have provisionally adopted this value. It is clear from the tabulated results that unless the constants of our relation are modified to an extent which does not seem permissible, the so-called short time scale of stellar evolution must be adopted and hence it is concluded that no star has radiated away any large fraction of its mass.

AXIAL ROTATION.

The radiation from a given region on a star's surface is normal to the level surface and in a perfectly uniform star the reaction forces always pass through the center of gravity; hence cannot produce rotation. However, if a star is broken up by any means, one might expect a marked asymmetry in its density and its center of figure would not coincide with its center of gravity. Thus reaction forces developed in certain

regions of a star's surface would not pass through its center of gravity and part of the reaction momentum might very well be converted into rotational momentum. Data are not available to test the idea and it is advanced here merely as a suggestion as to the origin of axial rotation of stars. Calculations show that if about 10^{-8} of the mass of the sun were radiated tangentially in a direction opposite to the instantaneous velocity of points on the sun's surface, then its present axial rotation might have been produced. Thus, for example, if the sun's center of gravity and figure were displaced by 10^{-2} of its radius, its rotation might be quantitatively explained.

THE EXPANDING GALAXY.

The observed mean radial velocity of all the stars, having due regard to sign, does not vanish as one might expect if the galaxy were in stable equilibrium. Campbell first pointed out that the mean radial velocity has a definite positive value and the residual velocity is usually known as the K term. The apparent recession of the stars from the solar system may be simply explained by supposing that the galaxy is expanding at a quite moderate rate.

The results of earlier paragraphs give a definite clue to the underlying mechanism; for by analogy one can readily see that if the temperature of a gravitationally unstable sphere of gas were constantly increased the sphere would expand. Thus, since we have just seen that the mean kinetic energy of every star in the heavens is increasing with time, we should expect the galaxy to expand.

Eddington's extension [7] of a famous theorem of Poincaré may be applied directly to great systems of stars and it states that

$$\frac{1}{2}\frac{d^2I}{dt^2} = 2W + \varphi, \tag{9}$$

where I is the moment of inertia of a given system of mass particles in a *non-steady* state, W is the total kinetic energy of the system, and φ is the gravitational energy.

For simplicity we start with a galaxy in equilibrium at a time $t = 0$ and having a moment of inertia I_0, a kinetic energy

[7] Eddington, M. N., 76, 525 (1916).

W_0 and a gravitational energy $\varphi_0 = -2W_0$. Now if the expansion is indefinitely slow, two-thirds of any added energy of the system will be used to overcome the gravitational forces while the other third will be retained in the form of kinetic energy. We have very clear observational evidence that the expansion is not slow and the time intervals we have to deal with are probably less than the relaxation time of the system. In order to take account of this fact we write $d\varphi/dt = -2q(dW/dt)$, where q is a factor which is dependent upon and increases with the distance of the selected star from the center of gravity of the galaxy. For statistical purposes q may be supposed to be a constant factor which is small for very rapid expansions and approaches unity for very slow changes. Thus, Eq. (9) may be written

$$\frac{d^2I}{dt^2} = 4(1-q)\int \frac{dW}{dt}\,dt \tag{10}$$

and this can be transformed to

$$\frac{d^2I}{dt^2} = \frac{4f^2b^2c^2(1-q)M}{2}\left(\frac{1}{M}\frac{dM}{dt}\right)^2 t^2 \tag{11}$$

so that on integration we have

$$I - I_0 = \frac{f^2b^2c^2(1-q)M}{12}\left(\frac{1}{M}\frac{dM}{dt}\right)^2 t^4 + \frac{dI}{dt_0}t. \tag{12}$$

In this first approximation it will be supposed that dI/dt_0 is small and can be neglected. Thus if G and G_0 are the radii of gyration of the final and initial states and $G_0 \ll G$ then it is found that

$$G = \frac{fbc(1-q)^{1/2}}{(12)^{1/2}}\left(\frac{1}{M}\frac{dM}{dt}\right)t^2. \tag{13}$$

or alternately

$$\frac{G}{ct} = \frac{fb(1-q)^{\frac{1}{2}}}{12^{\frac{1}{2}}}\frac{\overline{\Delta M}}{M}. \tag{13a}$$

From the form of this relation it may be seen that the effective linear dimensions of the galaxy are subject to a "uniform"

acceleration of

$$a = \frac{2fbc}{\left(\frac{12}{1-q}\right)^{1/2}}\left(\frac{1}{M}\frac{dM}{dt}\right) \tag{14}$$

and hence the rate of expansion of the galaxy was much less in the past then it is at present. It is important to note further that the effective expansion acceleration is proportional to $(1/M)(dM/dt)$ and hence the acceleration in the past was probably somewhat greater than it is at the present time.

Now if any system is subject to a uniform expansion, it is clear that

$$\frac{R}{G} = \frac{R_0}{G_0}, \tag{15}$$

where R and R_0 are the final and initial distances of any given object from an observer, G and G_0 the corresponding radii of gyration of the system. Thus,

$$\frac{dR}{dt} = \left(\frac{1}{G}\frac{dG}{dt}\right)R = v_r, \tag{16}$$

where v_r is the apparent recessional velocity of the object and observer. By the aid of Eq. (13) this may be written approximately as

$$v_r = \frac{2R}{\tau}, \tag{17}$$

where τ is the time interval from the beginning of the expansion to the present time or the age of the galaxy.

In the foregoing section we have seen how τ may be evaluated from Sears' data relating to the stars of our own galaxy so that Eq. (17) may be put in the approximate form

$$v_r = \frac{2^{1/2}fb\left(\frac{1}{M}\frac{dM}{dt}\right)}{\frac{\Delta V}{C}}R, \tag{18}$$

where the numerator can be estimated from the mean luminosity, mass and area of the radiating systems and the

denominator evaluated from the observed difference in velocity of early and late type stars. It is believed that data on binary systems will provide an independent method of calculating the denominator but this has not yet been done.

The result expressed in Eqs. (17) and (18) is of considerable interest because it is related to the so-called K term of Campbell and shows that stars in our own galaxy are statistically receding from us at a definite rate. Further, the forms of Eqs. (18) and (13) show that the velocity of recession will be greatest for the not too remote B type stars because they are radiating their mass the most rapidly. In applying the results to specific stars it must be remembered that q is also a variable.

From the compiled table of data we take

$$\frac{1}{M}\frac{dM}{dt_{\text{galaxy}}} = 10^{-20}, \qquad f = 0.64 \qquad b = 0.3 \qquad \frac{\overline{\Delta V}}{C} = 2 \times 10^{-1}$$

and find

$$(V_r)_{\text{galaxy}} = 1.35 \times 10^{-17} R. \tag{19}$$

Thus a representative star at 3,500 parsecs would, on the average, recede from the earth at a velocity approximating 1.3 km/sec. The value of the constant is subject to a moderate spread because of the uncertainty of some of the data but its indicated value fits in well with Campbell's observed data and the theoretical relation seems highly significant.

THE EXPANDING UNIVERSE.

The discovery by V. M. Slipher that the spectral lines of spiral nebulæ were displaced toward the red and the subsequent investigation by Hubble and Humason [8] which established a linear relationship between the line displacements and distances of the nebulæ has led to one of the most interesting conclusions of cosmogony. Astronomers and cosmogonists seem nearly agreed that the observed red displacements show that the Universe is in unstable equilibrium and is expanding at a nearly uniform rate.

So much has been written on the subject of the expanding universe from the theoretical point of view that we cannot

[8] Hubble and Humason, *Astrophys. Jour.*, 74, 43 (1931).

hope to review earlier work in a single paragraph. It is sufficient to point out that the earlier investigators have nearly all attempted to solve the problem without considering definite physical mechanisms which are capable of producing the observed phenomena and have preferred to assign special properties to space, etc., in order to attain their goal. This procedure is so arbitrary and unsatisfactory that the author has examined various physical processes which are energetically capable of producing the observed effects. In the present discussion we need not assign special properties to space, but may suppose that light travels unimpeded along straight lines in an Euclidian space. Thus, one must conclude that the observed expansion of the universe is real and that some hitherto neglected source of potential energy is constantly pouring kinetic energy into the universe in such a way that the nebulæ may overcome the gravitational forces and expand outward. The non-symmetrical radiation from nebulæ that have suffered fission provides an adequate means for supplying the required kinetic energy.

The observational data regarding the dimensions and mean spacing of the extra galactic nebulæ show that the diameters of typical nebulæ are about 2 per cent. of their mean spacing. Moreover, the present rate of recession of each nebula from its neighbors is such that by extrapolating backward it is found that all nebulæ must have been in contact some 10^{10} years ago. Therefore, apparently all the matter of the present observed universe was once contained in a single diffuse parent super-nebula. It may be assumed that this parent super-nebula possessed angular momentum and as a result of its rotation or some other means, the parent nebula broke up into a great number of extra galactic nebulæ. The parent super-nebulæ may be supposed to have had, initially at least, properties comparable to a diffuse gaseous star and hence the internal temperatures must have been even greater than those estimated for the center of a white dwarf. Evidently, the formation of many nebulæ from such a parent by any sort of a fission process will result in a highly unsymmetrical distribution of internal temperature. The radiation from the surface of the nebula will also be unsymmetrical and the conditions for producing accelerations by

radiation recoil are automatically established. It is impossible to estimate the exact amounts of energy radiated from the hot and cold faces of the nebulæ at the present time, but the cataclysms that brought about the thermal asymmetries were energetic and the difference in radiation between the two faces would therefore appear to be an appreciable fraction of the total radiation. We are, therefore, considering first order effects.

Carrying through a calculation identical in form with that of Eq. (9) and adopting values for τ from Table I as deduced from the motions of stars in our own galaxy, then by Eq. (17)

$$V_r = .6 \times 10^{-17} R.$$

This result is to be compared with Hubble's observed data [8] which lead to

$$V_H = 1.8 \times 10^{-17} R.$$

Due to the difficulty in evaluating some of the constants it is considered that this result is in agreement with observation.

There is little a priori reason for supposing that the motions of nebulæ will be governed by exactly the same laws as the stars since their structures, now at least, are much different. Yet the agreement between the results of the calculations for the galaxy and observational data relating to nebulæ are sufficiently striking that one may suppose that radiation reaction forces play, perhaps, a major role in guiding the motions of nebulæ.

It is considered that the galaxy and the extra galactic nebulæ were born some 10^{10} years ago of a parent supernebulæ in a manner much as the stars are believed to have been born of ordinary nebulæ. Such an hypothesis readily accounts for the deep seated thermal asymmetries necessary to make radiation reaction forces important because such a birth process is simply a special case of the stellar fission processes considered above. The subsequent history of the nebulæ is described by exactly the same expressions derived for the galaxy and hence leads immediately to Hubble's empirical relation. The form of the expressions that we have derived shows that initially the rate of expansion of the universe was small and that as time goes on it will expand

faster and faster until radiation recoil effects approach zero. Thus it seems that the universe must have originated from a parent super-nebulæ as a result of a slow evolutionary process which must have occupied thousands of millions of years. The parent bodies are disintegrated and gone and we now witness only the hurried motions of the second (nebulæ), third (stars), fourth (planets) and fifth (satellites) generations. The evidence that each generation is produced from the earlier one by a fission process is, we think, fairly good.[4]

It seems clear that the radiation from stars and nebulæ must eventually drop to small values and the "uniform" acceleration we have considered must cease and will perhaps be followed by a general condensation of the cold stars and nebulæ. The condensation will proceed for a long period and the final state of the universe may well be a highly condensed system of relatively cold bodies describing gravitational orbits about their common center of gravity with velocities comparable to that of light.

REMARKS.

The main argument of this paper rests on the observational evidence that we have concerning the birth of stars and their subsequent evolution into single and multiple star pairs by a fission process. If stars are not born from the parent nebulæ by fission or subsequently divide as a result of rotational instability or other equivalent process, then the mechanism is probably unimportant, unless some unconsidered phenomenon gives rise to deep seated thermal inhomogeneities. The asymmetry may well be equalized by conduction processes in a much shorter time than the age of a star, possibly 10^8 years. In such a circumstance it would be necessary to solve both the conservative and non-conservative cases and appropriately combine them. In either case. the mechanism considered could account for the observed expansion and in this first approach to the problem it seems immaterial whether one thinks of a very rapid initial expansion covering a period of perhaps 10^8 years with a long period of decline or a continuous process of the type just examined in detail.

In this preliminary analysis several simplifying assumptions have been made in order to bring out clearly the essential

physics. It is, for example, not perfectly proper to consider the quantities b, q and dM/dt as being constants because each probably changes slowly with time. We can, however, see physically that the assumptions will not change the form or order of magnitude of the result. It is believed that every bit of evidence available definitely points to the universality of stellar and nebular break-up; hence radiation reaction forces are likely to be quite important in guiding the evolution of the universe.

From the analysis of the above phenomena it appears that the universe is actually expanding and that the observed red shifts are, in fact, true Doppler displacements. Further, it appears that the ages of the solar system, the galaxy, and the universe are all comparable and of the order of 10^{10} years. This period of time is so short that the stars in the heavens have changed but little since the beginning of time and have radiated an inappreciable fraction of their total mass.

A SHORT ACCOUNT OF THE THEORY OF LUBRICATION.[1]

III. DIMENSIONAL THEORY, WITH APPLICATIONS.

BY

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The following explanation of dimensional analysis, including the theory of model experiments, may be of general interest outside the immediate field of lubrication problems, on account of the steadily increasing use of the dimensional method in almost every branch of engineering research. It has been found especially helpful in planning and interpreting experiments in elasticity, fluid dynamics, and heat transmission, where the conditions met in practice are sometimes far too complex for a purely mathematical solution; or even for a direct experimental solution by the orthodox procedure of varying each factor separately.

The particular reasons leading up to the use of dimensional theory in lubrication may best be understood after reviewing, briefly, some of the results and limitations of the hydrodynamic theory.

PRESENT STATUS OF HYDRODYNAMIC THEORY.

The hydrodynamic theory of lubrication, in its classical form, is represented by the differential equation for pressure distribution, due to Reynolds, Eq. (7) of Section II. This equation, it will be recalled,[2] rests upon such physical concepts

[1] Continued from the June and July issues of the JOURNAL, pages 677 and 693, respectively. Based upon the public lectures given at Brown University, 1934, and at Yale University, 1935; the latter series under the auspices of the New Haven Section, American Society of Mechanical Engineers. The remaining installment, to appear in September, deals with the theory of the temperature rise and temperature distribution in bearings.

[2] Reynolds' equation, which need not be repeated here, is a linear equation of the second order underlying the principle of the oil wedge, or converging film. The separate quantities appearing in it are the film pressure, film thickness, and viscosity at any point (x, z) together with the relative velocity of the bearing surfaces.

as Newton's law of viscosity, the conditions for statical equilibrium, and the equation of continuity. In applying Reynolds' equation, it is to be integrated and solved in conjunction with other relations that may be needed for defining the particular conditions of each problem, as for example the system of applied loads, the geometry of the bearing surfaces, and the performance characteristic under investigation.

The steps necessary in applying Reynolds' equation have been illustrated[3] by our discussion of Sommerfeld's theory, chosen for this purpose because of its simplicity and visible logic, although the situations where the Sommerfeld conditions can be completely realized are of rare occurrence. Numerous other applications have also been published, including full and partial journal bearings of every type; thrust bearings, and gear teeth.

Any satisfying report of all these applications might fill a large volume, even if it were a purely summarizing report not undertaking to advance the subject. With but few exceptions the available literature is exceedingly hard reading. The most evident limitations of the hydrodynamic theory in its present state of development and application[4] may be considered under three heads, (1) the point of view of the analysis; (2) physical limitations; and (3) geometrical limitations.

1. Some of the most ingenious and successful investigations, such as Kingsbury's study of optimum conditions, Ref. 45 of Section II, have been conducted strictly from the viewpoint of bearing design. The results therefore are not always directly applicable in calculating the probable performance of a bearing of any fixed design, or in selecting the most suitable lubricants for existing machinery.

2. The treatment is usually limited to a steady state, with constant viscosity; and in most investigations, even when side leakage is taken into the picture, the effects of negative pressure are dealt with in some arbitrary or artificial way.

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[3] See also Appendix 1 of the recent paper by M. Stone, Ref. 22.

[4] That the proper application of hydrodynamic theory is by no means self-evident or standardized, as yet, may be seen upon comparing the results obtained by Needs on the 120° bearing with Swift's treatment of negative pressures (Refs. 47 and 51 of Section II); or again by comparing Howarth's latest chart for the full bearing with the theory of Orloff (Refs. 52 and 53 of Section II).

3. The bearing surfaces are assumed perfectly smooth and rigid, and of some ideally simplified geometrical form; the applied loads, other than the driving torque, reducing to a single resultant force, conveniently located for purposes of calculation.

Because of these limitations and in order to verify the laws of lubrication there is a constant demand for direct experimentation. Swivel-chair experimental work is both easy and economical, but before any project can be carried through to completion in the laboratory a host of new difficulties may arise. Questions associated with the accuracy and finish of the bearing surfaces and the methods of temperature measurement will immediately come to mind. We wish, however, to call attention especially to the large number of variables involved in lubrication experiments. The number of observations necessary for exploring the field in connection with any one type of machine element may be very considerable, and the expense correspondingly great, when the separate factors are varied over the full range one at a time.

Dimensional theory offers a possible escape from both sets of difficulties by means of a combined mathematical and experimental approach, to be outlined below.

DYNAMICAL SIMILARITY.

The best known application of dimensional theory is the principle of dynamical similarity. Froude's law of comparison for ship models and Rayleigh's equation for wind tunnel experiments are two of the most interesting historical examples. These same methods for experimenting on reduced scale models which have been successful in naval architecture and aeronautics may also be applied in lubrication research.

Froude's law for towing tank experiments states that the wave-making resistance R opposing the movement of a boat through the water at a constant velocity v may be calculated from the resistance R_m of a geometrically similar model by the law of comparison

$$\frac{R}{R_m} = \left(\frac{D}{D_m}\right)^3, \tag{1}$$

in which D and D_m are the linear dimensions of the original

and the model respectively. In order for this law to be valid it is necessary to tow the model at a reduced speed v_m given by

$$\frac{v_m}{v} = \left(\frac{D_m}{D}\right)^{1/2}. \tag{2}$$

Eq. (2) is known as the condition for similarity. The two speeds v_m and v are called corresponding speeds. Now the displacements of geometrically similar vessels are proportional to the cubes of their linear dimensions. Froude's law may therefore be expressed by the statement that the wave-making resistances are proportional to the displacements, provided the immersed surfaces of the model and original are geometrically similar; and provided the resistances are compared, not at the same speed, but at speeds proportional to the square root of the length. In practice it is necessary to correct the measured pull of the model on the tow line for the skin-friction, or fluid resistance other than wave-making resistance, before applying the law of comparison. Froude's law, given above without proof merely as an example, has long been used as one of the basic working principles of naval architecture.

Rayleigh's equation deals with the resisting force, R, experienced by a totally immersed body of any fixed geometrical shape and linear dimension, D, moving at a constant velocity v through a stationary medium like air or water. Let ρ denote the density and μ the viscosity of the fluid. The equation may then be written, as shown by Lord Rayleigh,

$$R = \rho v^2 D^2 \phi \left(\frac{Dv\rho}{\mu}\right), \tag{3}$$

in which ϕ is a symbol for some unknown function of the combination variable in parentheses. The specific form of thig function, whether a reciprocal or power series or somethine else, remains to be discovered by experiment. Writing ths equation over again for the model experiment and dividing one by the other, it is seen that the unknown function cancels out, leaving

$$\frac{R}{R_m} = \frac{\rho}{\rho_m}\left(\frac{v}{v_m}\right)^2\left(\frac{D}{D_m}\right)^2 = \frac{\rho_m}{\rho}\left(\frac{\mu}{\mu_m}\right)^2, \tag{4}$$

provided the comparison is made at corresponding speeds defined by

$$\frac{v_m}{v} = \frac{\mu_m}{\mu} \cdot \frac{\rho}{\rho_m} \cdot \frac{D}{D_m}, \tag{5}$$

or $Dv\rho/\mu = \text{Const.}$ If the test is conducted in a modern compressed air wind tunnel under a pressure of 20 atmospheres so that $\rho_m/\rho = 20$, Eq. (4) shows, neglecting the very slight effect this pressure might have on the viscosity of the air, that the head resistance or drag of an aircraft will be 20 times the force on the model. The condition for similarity, Eq. (5), requires that the air speed in the tunnel be adjusted to 1/2 the speed of flight in the case of a model 1/10 the size of the original.

The actual, visible similarity of the stream lines and eddies under such conditions was demonstrated by photographs taken at the National Physical Laboratory in England and published many years ago. Thus the simple formulas of dynamical similarity when properly applied enable us to predict the behavior of large bodies from observations on smaller ones, and to predict the behavior of one kind of fluid from measurements made on another, even when the motions involved are too complex to permit the integration of differential equations.

Two journal bearings are dynamically similar under normal operating conditions if they are geometrically similar, and running at the corresponding speeds given by

$$\frac{N_m}{N} = \frac{P_m}{P}\left(\frac{\mu}{\mu_m}\right), \tag{6}$$

or $\mu N/P = \text{Const.}$, where N denotes the number of revolutions per unit time, P the load per unit area, μ the effective viscosity, and the subscript, as before, refers to the model. Under these conditions the two bearings will have the same coefficient of friction and the same relative film thickness regardless of absolute size; in fact, all performance characteristics which can be expressed by dimensionless ratios will be identical.

The proof of the principle of similarity with its application to the Froude, Rayleigh, and lubrication propositions follows directly from the theory of dimensions.

DIMENSIONAL THEORY EXPLAINED CONCRETELY BY CONSIDERING THE FLOW THROUGH PIPES.

Let it be required to determine the relation between the pressure drop p and the flow velocity v in a pipe length L and diameter D, carrying an incompressible fluid of density ρ and viscosity μ. If there are no other physical quantities whose variation could affect the pressure drop in pipes of a given geometrical shape when v, D, ρ, and μ are already fixed, we may express the relation qualitatively by saying that for all geometrically similar pipes, the pressure drop is some definite function of v, D, ρ, and μ. This may be written

$$p = F(v, D, \rho, \mu), \tag{7}$$

where F denotes the function in question. The form of the function F may be somewhat different for smooth and rough pipes, and for pipes of circular as compared with elliptical or rectangular cross section; certainly the numerical coefficients will be affected by the roughness and by the shape of the cross section.

Whatever the form of the function may turn out to be, if the specific formula symbolized by Eq. (7) is a correct and complete physical equation, it should tell the same story in any system of units. Substituting $v = 8$ feet per second, $D = 0.333$ foot, etc., may give, for example, $p = 120$ pounds per square foot. If so, we should expect, upon working it through a second time using metric units, to obtain the equivalent of 120 pounds per square foot. That is to say, upon substituting $v = 2.44$ meters per second, $D = 0.1015$ meters, etc., we should obtain $p = 587$ kilograms per square meter. In translating a poem from English into French, then into German and back to English, we expect variations, and much amusement may be derived from such a game. The analogous inconsistency in working with physical equations would be intolerable, and may be taken as proof of a mistake. Incomplete equations, where some physical factor has been suppressed, i.e., treated as a numerical constant, are familiar in engineering; but such equations are valid only in a designated system of units, and need not be further considered here. In order for a physical equation to give the same ultimate result in any system of units it must be a complete equation,

and all terms on both sides must have the same dimensions. This is known as the principle of dimensional homogeneity.

By the *dimensions* of any physical quantity are meant the *exponents* of the fundamental units in the expression by means of which the unit of this quantity is derived or defined. We may define the unit of area as the square of the unit of length; the unit of acceleration as the first power of the length unit multiplied by the minus second power of the time unit; and so on. Thus the dimensions of area are *two* with respect to length; of acceleration *one* with respect to length and *minus two* with respect to time; etc.

The dimensions of some of the more important mechanical quantities are collected for reference in Table 1. They have

TABLE 1.

Dimensions of Some Mechanical Quantities.

Symbol.	Quantity.	Dimensions.	Symbol.	Quantity.	Dimensions.
C	Clearance (total)	L	b	Pressure coefficient of viscosity	L^2/F
C	Compressibility	L^2/F	c	Clearance (radial)	L
D	Diameter or linear dimension	L	e	Eccentricity	L
E	Young's modulus	F/L^2	e	Efficiency	1
F	Frictional resistance	F	f	Coefficient of friction	1
G	Generalized variable ZN/P	1	g	Gravity (acceleration)	L/T^2
H	Power	FL/T	h	Film thickness	L
L	Length	L	m	Mass	FT^2/L
M	Moment of force	FL	p	Pressure	F/L^2
N	Revolutions per unit time	$1/T$	s	Sommerfeld variable	1
			t	Time	T
P	Load per unit area, or pressure	F/L^2	v	Flow velocity	LT
Q	Rate of flow	L^3/T	w	Weight per unit volume	F/L^3
R	Rate of shear	$1/T$	x	Film thickness (minimum h)	L
S	Shearing stress	F/L^2			
S	Surface tension	F/L	θ	Angle	1
T	Tooth load per unit width	F/L	μ	Viscosity	FT/L^2
T	Torque	FL	ν	Kinematic viscosity	L^2/T
U	Surface speed	L/T	ρ	Density	FT^2/L^4
W	Load (total)	F	σ	Poisson's ratio, or specific gravity	1
W	Work	FL	ω	Angular velocity	$1/T$
Z	Viscosity	FT/L^2			

been expressed for convenience in terms of force, length, and time, (F, L, T), although other combinations of three fundamental units would be equally good. When a quantity is

dimensionless, it is customary to write 1 in place of the expression $F^{\circ}L^{\circ}T^{\circ}$. To indicate how the dimensions of an unfamiliar quantity may be worked out, consider viscosity. We must go back to the original definition or to some known formula involving the new physical quantity, as for example Eq. (3) of Section I. Viscosity is defined as the ratio of shearing stress to rate of shear. Stress is force divided by area and therefore has the dimensions of force divided by length squared. Rate of shear may be taken as velocity divided by distance, or angle divided by time, so it has the dimensions of time to the minus one. Combining numerator and denominator, viscosity has the dimensions of force multiplied by time and divided by the square of a length. As a check we recall that the units of viscosity were given in Table 1 of Section I as pound seconds per square inch, and kilogram seconds per square meter, in the respective systems of units.

In applying the principle of homogeneity to Eq. (7) we may first suppose the function F expanded into a series of terms each constructed in the simplest form, the variables v, D, etc., entering these separate terms only with constant exponents. This involves the mathematical assumption that any curve connecting p with such a variable as v may be approximated as closely as desired by a power series (Ref. 1), provided there is no restriction as to the values of the exponents or the number of terms. The exponents are represented by a, b, c, $\cdots$ in any one term of the summation, but may have different numerical values in successive terms.

With this understanding the equation may be written

$$p = \Sigma N \cdot v^a D^b \rho^c \mu^d, \tag{8}$$

in which N is some numerical coefficient (a pure number), presumably different for the different terms in the series; and Σ is the summation sign meaning that all the terms are to be added together to produce the value of p. Now since the dimensions of all terms on the right must be identical with the dimensions of p we may disregard the factor N, which is without dimensions, and write for any one term [5]

$$p : v^a D^b \rho^c \mu^d. \tag{9}$$

[5] The colon is used for convenience to denote dimensional equivalence in place of the more conventional square brackets with equality sign.

Substituting from Table 1,

$$\frac{F}{L^2} : \left(\frac{L}{T}\right)^a L^b \left(\frac{FT^2}{L^4}\right)^b \left(\frac{FT}{L^2}\right)^d. \tag{10}$$

Since in (10) the dimensions of force must be the same on both sides,

$$l = c + d; \tag{11}$$

since the dimensions of length must also be the same on both sides,

$$-2 = a + b - 4c - 2d; \tag{12}$$

and finally from the time dimensions,

$$0 = -a + 2c + d. \tag{13}$$

Solving (11) to (13) simultaneously for any three of the four unknowns in terms of the remaining one,

$$\left.\begin{aligned} a &= 2 - d, \\ b &= -d, \\ e &= l - d. \end{aligned}\right\} \tag{14}$$

Substituting from (14) into (8) and taking factors with numerical exponents outside the summation,

$$p = \rho v^2 \Sigma N \left(\frac{Dv\rho}{\mu}\right)^{-d}. \tag{15}$$

This is as far as we can go except to put the result in a more convenient form. Since the values of N and d for the various terms are unknown and the number of terms is unknown, all that can be said about the summation in (15) is that it represents some unknown function of the single variable $Dv\rho/\mu$. Let the function be symbolized by ϕ; then

$$p = \rho v^2 \phi \left(\frac{Dv\rho}{\mu}\right). \tag{16}$$

For excessively turbulent motion the pressure drop, or fluid friction, is known from hydraulic experiments to be very nearly proportional to the square of the velocity. In the limit when $p \propto v^2$ Eq. (16) shows that ϕ must reduce to a constant; the pressure drop will then be proportional to the

density, and independent of the viscosity. In the opposite limiting case, that of pure stream line motion, as in capillary flow, experiment shows that the pressure drop is proportional to the first power of the velocity. In this event ϕ must be a reciprocal function, in order to bring down the exponent of v from 2 to 1; leading to the conclusion that the pressure drop is directly proportional to the viscosity, and independent of the density.

The foregoing analysis has been restricted to geometrically similar pipes, the ratio L/D being treated as a constant and therefore not appearing in the equations. If, however, L is included among the initial variables of Eq. (7) we should find in place of (16) the more general relation

$$p = \rho v^2 \psi \left(\frac{Dv\rho}{\mu}, \frac{L}{D} \right), \tag{17}$$

where ψ is an unknown function involving two independent variables, instead of only one. In the case of stream line motion where $p \propto v$, the function ψ reduces to $\mu/Dv\rho$ multiplied by some function of L/D. Finally when conditions are uniform along the pipe or tube, so that $p \propto L$, Eq. (17) reduces to

$$p = \text{Const.} \frac{\mu v L}{D^2}. \tag{18}$$

To check this by comparison with Poiseuille's law, Eq. (10) of Section I, we may start with the expression for the rate of flow in volume units per unit of time, $Q = \pi D^2 v/4$. Solving (18) for v and substituting,

$$Q = \text{Const.} \left(\frac{p}{L} \right) \frac{D^4}{\mu}. \tag{19}$$

The numerical value of the constant cannot be found by dimensional reasoning, and will naturally depend on the shape of the cross section. For the circular cross section, we know from Poiseuille's law that the constant of (19) is equal to $\pi/128$. It is interesting and significant that the dimensional derivation of (19) is not restricted to cross sections of any particular geometrical shape.

Another important result obtained from Eq. (16) is

Reynolds' criterion for the critical velocity at which stream line motion changes over into turbulent or eddying motion with gradually increasing speeds. Any sudden change in the law of resistance corresponds to a break in the curve for $p/\rho v^2$ plotted against $Dv\rho/\mu$; and therefore occurs with different fluids, or in different pipes which are geometrically similar, whenever $Dv\rho/\mu$ passes through a fixed numerical value. Let K denote this value, while v_c is the critical velocity. It follows that

$$v_c = \frac{K}{D}\left(\frac{\mu}{\rho}\right); \qquad (20)$$

hence the critical velocity is directly proportional to μ/ρ and inversely as the diameter of the pipe.[6]

PHYSICAL SIMILARITY AND DIMENSIONLESS VARIABLES.

Equations (3) and (16) are representative of the general form in which any equation will appear when deduced by the method of dimensions. Conversely any physical equation which is correct and complete, whether arrived at theoretically or empirically, must be reducible to this form. An equation of the same type is obtained for Froude's problem assuming that the wave-making resistance R for geometrically similar vessels depends only on the linear dimension D, the velocity v, the density ρ, and the gravitational acceleration g or weight per unit volume, w. The corresponding equation for the coefficient of friction of the journal bearing may be written

$$f = \phi\left(\frac{\mu N}{P}\right); \qquad (21)$$

and is deduced from the assumption that the coefficient depends only on μ, N, P and the journal diameter D.

Thus in all four examples we find the dependent variable in which we are especially interested on the left, and some unknown function on the right. Although the form of the

[6] The ratio of viscosity to density, μ/ρ, which so frequently appears in flow equations, though but rarely if ever in a lubrication problem, is commonly known as the *kinematic* viscosity and denoted by ν (nu). The term *lentor* has been proposed by Dr. G. Barr of the National Physical Laboratory (Ref. 42 of Section I) in place of kinematic viscosity, to avoid confusing this property with viscosity.

function may be unknown, the argument of the function, or combination variable enclosed in parentheses, is definitely ascertained by means of the dimensional theory. This is all that is necessary for the practical application of the similarity principle. The model experiment and the full scale experiment are said to be dynamically similar when the conditions of the model experiment are so arranged that the argument of the unknown function has the same numerical value in both experiments. When this condition of similarity is met, the unknown functions cancel out upon dividing the equation for the full scale phenomenon by the equation for the model experiment. The resulting equation is known as the law of comparison.

The principle of dynamical similarity has been extended to include thermal and electrical applications. In this form it is known as the principle of similitude or of physical similarity. Further discussion will be found in Refs. 1, 2, 5–8, 10, 11, 20. A more interesting subject for future study and development can hardly be imagined in the entire field of engineering research. At the same time it dates back, in its origins, to Newton and Fourier and some of the earlier papers of Lord Rayleigh.

In the historical development of the subject it gradually became apparent that such applications as Froude's law, and Rayleigh's aerodynamic equation, and the principle of similarity itself are special cases of a more general proposition. This has been called the Π-*theorem* by Edgar Buckingham because of his use of the symbol Π (Greek capital *pi*) for a *dimensionless product*. The theorem states that the most general form of any correct and complete physical equation consists in some relation connecting all of the *independent* dimensionless products which can be constructed by combining the separate quantities entering the problem; and it further tells what this maximum number of dimensionless products will be. It is equal to the number of quantities minus the number of fundamental units needed in measuring them, or $i = n - k$.

Rayleigh's equation, for example, may be rewritten

$$\frac{R}{\rho v^2 D^2} = \phi\left(\frac{Dv\rho}{\mu}\right), \tag{22}$$

which is merely a relation connecting the two dimensionless

products $\Pi_1 = R\rho^{-1}v^{-2}D^{-2}$ and $\Pi_2 = Dv\rho\mu^{-1}$. Only two such products, truly independent of each other, can be formed by combining in any way the five separate quantities R, v, D, ρ, and μ. Since it requires three fundamental units such as force, length, and time to measure these five quantities, the theorem tells us that only $5 - 3$ or 2 independent products are to be anticipated. If these can be found by trial, the problem is solved; and there is no need of actually going through the routine steps indicated by Eqs. (8) to (15) every time. Other short cuts are available in the literature (Refs. 4, 6).

In the lubrication problem we start with the qualitative assumption that f may be some function of μ, N, P and D. The problem as thus restricted involves at the outset five mechanical quantities, which are of such a nature as to require three fundamental units for an absolute system of measurements. Again, as it happens, there will be two dimensionless products. Obviously f itself, already dimensionless, is one of them. By trial it is found that the product $\mu NP^{-1}D^{\circ}$ or $\mu N/P$ is dimensionless, hence the relation sought for is that given by Eq. (21); and the coefficient of friction is independent of the size of the bearing.

We are thus led to see that physical equations are necessarily relations between dimensionless variables. This criterion may be usefully applied (1) as a check on the accuracy of any given equation; (2) as a theoretical starting point for deducing new relationships; (3) as a basis for model experiments, in the form of the principle of similarity; (4) as a method of building up the most general empirical equation to represent a given curve; and (5) as a means for reducing to a minimum the number of experimental variables required in any proposed investigation.

Since the dimensional method is essentially a logical machine which can give back only what is put in, any doubt regarding the result must be settled by re-examining the list of quantities selected at the start.[7] The degree of success to

[7] The story of the bishop's hat serves to emphasize this important point. It is said that the late Phillips Brooks, after attending a meeting at the Parker House, called for his silk hat at the cloakroom; and was much impressed by the ability of the attendant on duty to hand back the correct articles without any checks. "How do you know," whispered the kindly bishop, "that this is my hat?" "'Deed, sah," came the quick reply, "I *don*' know 'at's yo' hat. I only knows it's de hat you done giv' me."

be expected in the use of the method depends on our common sense and background of experience with physical facts as applied, in each particular case, in drawing up the original qualitative equation.

THICK FILM LUBRICATION OF JOURNAL BEARINGS.

In the earliest applications of dimensional reasoning to the journal bearing problem (Ref. 3) the treatment was carefully restricted to thick film lubrication, assuming a uniform viscosity throughout the film, and assuming rigid bearing surfaces, thereby excluding the combination of a very heavy load with a very low speed. Even under those limitations the results were found useful, and in present day notation are referred to as ZN/P relations. Thus Eq. (21) may be written

$$f = \phi\left(\frac{ZN}{P}\right) = \phi(G), \tag{23}$$

where Z has been adopted in place of μ for the effective viscosity in the film, and G denotes[8] the generalized variable ZN/P. The proof given above under (21) assumed *normal operating conditions*.[9]

The function ϕ is the same for all bearings which are strictly geometrically similar, including any specifications needed for locating the line of application of the load. If, however, there is a resultant external couple about an axis perpendicular to the axis of rotation, such as might be caused by belt pull, overhanging load, or misalignment, the problem becomes more complicated. Let M denote the moment, or torque, due to this couple. It is necessary, then, to add the new quantity M to the original list, writing for the qualitative equation

$$f = F(Z, N, P, D, M). \tag{24}$$

Here are $n = 6$ quantities requiring $k = 3$ fundamental units, therefore $i = n - k = 3$. In addition to $\Pi_1 = f$ and $\Pi_2 = G$

[8] The use of G for ZN/P is analogous to the long established use of the coefficient f to represent the dimensionless variable $2T/DW$, as indicated by Eq. (20) of Section I.

[9] Conditions such that lubrication performance depends only on size, shape, speed, load, and viscosity.

we write down by inspection $\Pi_3 = M/D^3P$, and the result becomes

$$f = \phi\left(G, \frac{M}{D^3P}\right); \tag{25}$$

reducing to (23) when $M = 0$. From (25) it is clear that the coefficient is no longer the same for large and small bearings, unless it should happen that M is proportional to D^3P. The condition for similarity is that both G and M/D^3P shall have the same values for the model and the full-sized bearing.

Thus it appears that factors ordinarily assumed negligible may be taken into account by forming the appropriate dimensionless products, which are then treated as additional variables in the same category with G. Other examples of such factors are the effect of a static supply pressure p_0 in excess of atmospheric pressure, represented by $\Pi_4 = p_0/P$; the dynamical effect of forced lubrication, depending both on p_0 and the density ρ, for which Π_4 may be retained and $\Pi_5 = \rho D^2N^2/P$ added; the surface tension of the lubricant, S, influencing its retention in the clearance space, for which $\Pi_6 = S/PD$; the compressibility of the lubricant, C, for which $\Pi_7 = CP$; the atmospheric pressure p_1, not necessarily negligible even if constant, for which $\Pi_8 = p_1/P$; and the rate of feed Q in the case of restricted supply, leading to the product $\Pi_9 = Q/D^3N$. Any effect of turbulence in the film would be represented by Π_5.

The effect of periodic fluctuations of load in the connecting rod bearings of the automobile, and other reciprocating machines, has apparently not yet been investigated by the method of dimensions. The generalized variable G will be retained, but other variables must be added. Further deviations from normal operating conditions, such as non-uniform viscosity and shaft deflections, are considered below in connection with thin film lubrication. These effects may occasionally become important even when there is a relatively thick film present.

Returning to the normal conditions under which Eq. (23) is applicable, we may next inquire regarding other performance characteristics besides the coefficient of friction. One such characteristic is the relative film thickness, x/c, at the

point of nearest approach. Proceeding as before it is found that

$$\frac{x}{c} = \psi\left(\frac{ZN}{P}\right) = \psi(G), \tag{26}$$

where ψ is unknown, but the same for geometrically similar bearings.

If the load capacity, P_0, is defined as that value of P for which the film thickness is reduced to some arbitrarily chosen value x_0, (26) may be written

$$\frac{P_0}{ZN} = \text{funct.}\left(\frac{x_0}{c}\right) = \text{Const.}, \tag{27}$$

since any function of a constant is itself a constant. Thus it has been proved, with the aid of dimensional theory alone, that the load capacity of any bearing, however complicated in shape, is directly proportional to the viscosity, and also to the speed.

While the coefficient of friction, relative film thickness, and load capacity are the performance characteristics of chief interest, it follows from the Π-theorem that any such characteristic of geometrically similar bearings which can be expressed as a dimensionless ratio, or product, is determined solely by the value of G under the normal operating conditions that we are now considering. Other examples are: (1) angular location of the point of nearest approach, and of the points of maximum and minimum pressure; (2) the rate of oil flow, Q, due to the pumping action of a bearing, expressed by its ratio to the clearance volume or any other fixed volume multiplied by N, the speed in revolutions per unit time; and (3) the relative film pressure at any stated point of the bearing, expressed by its ratio to the load per unit area, P.

COMPARISON WITH HYDRODYNAMIC THEORY.

Any equation for lubrication performance obtained from the hydrodynamic theory must necessarily be a particular case of the corresponding general equation from dimensional theory. For convenience in making such comparisons Eqs.

(23) and (26) may be written out more explicitly

$$f = \phi\left(G, \frac{C}{D}, \frac{L}{D}\right) \tag{28}$$

and

$$\frac{x}{c} = \psi\left(G, \frac{C}{D}, \frac{L}{D}\right); \tag{29}$$

the requirement for geometrical similarity now being removed so far as concerns the clearance-diameter and length-diameter ratios. Petroff's formula, for example,

$$f = 2\pi^2\left(\frac{D}{C}\right)G \tag{30}$$

is a particular case of (28) when $L/D = \infty = \text{Const.}$ The Sommerfeld film thickness curve, Fig. 6 of Section II, in which x/c is plotted against $(D/C)^2G$ will be recognized as a special case of (29) with $L/D = \infty$.

Equations (28) and (29) are further illustrated by Figs. 1 and 2 for the 120° bearing, based on the work of S. J. Needs (Ref. 51 of Section II). For convenience G' instead of G has been taken as the plotting variable, where G' denotes the value of G in the particular system of mixed units now so commonly used (Z in centipoises, N in revolutions per minute, and P in pounds per square inch, Refs. 9, 15). The relation between G, which has the same value in any system of normal units,[10] and G' is given to three significant figures [11] by

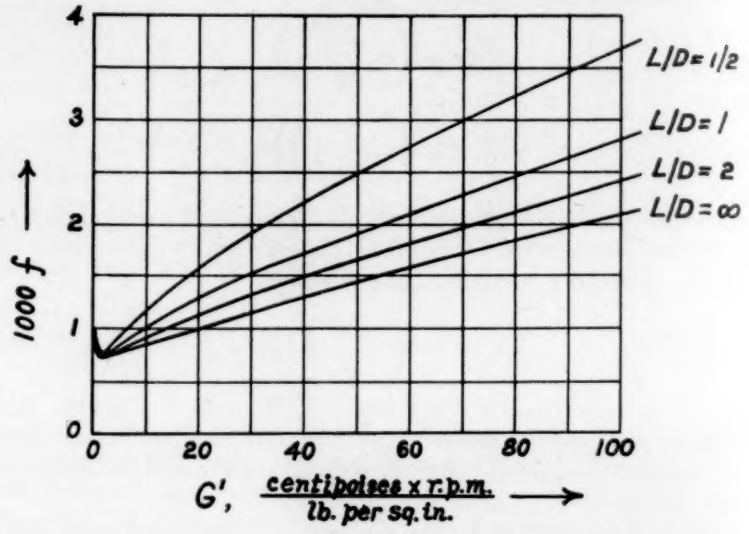
$$\left.\begin{aligned} G &= 2.42 \times 10^{-9}\, G' \\ G' &= 4.14 \times 10^{8}\, G \end{aligned}\right\}. \tag{31}$$

Additional curves for other clearance ratios may be constructed from Figs. 1 and 2, since it was shown by Needs that for any one value of L/D, the quantities $(D/C)f$ and x/c depend only on $(D/C)^2G$ regardless of the separate values of C/D.

[10] Normal units are derived from the fundamental units by formulas in which the proportionality constant is equal to one. The c.g.s. and inch, pound, second systems are examples; but a system based on the inch as the unit of length together with the square foot as the unit of area would not be. Any dimensionless variable has the same value in all systems of normal units, and such units are understood if the contrary is not stated.

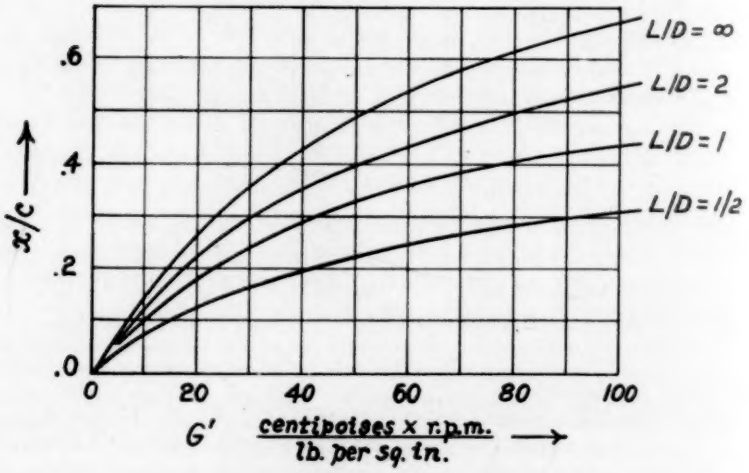
[11] Based on the conversion factor 1 lb. sec./in.^{2} = 68,950 poises.

FIG. 1.



Coefficient of journal friction for 120° centrally loaded bearings, computed from paper by S. J. Needs; $f = \lambda$, $L/D = (\pi/3)w/l$, $C/D = \eta/a = 1/1000$.

FIG. 2.



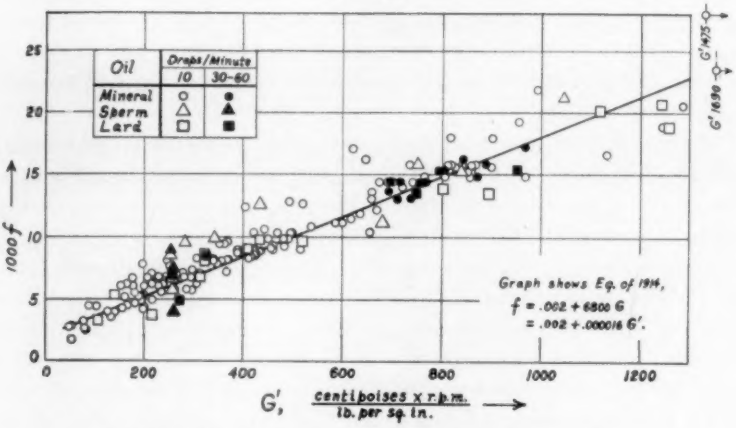
Relative film thickness for 120° centrally loaded bearings computed from paper by S. J. Needs: $x/c = h_0/\eta$, $L/D = (\pi/3)w/l$, $C/D = \eta/a = 1/1000$.

From these examples it will be clear that there can be no inconsistency between dimensional theory and the classical form of the hydrodynamic theory. The dimensional form of the hydrodynamic theory is not a competitive theory, but merely a tool for investigation, like the etching reagent in metallography.

COMPARISON WITH EXPERIMENT.

Figure 3 shows results obtained by the author from tests on a full journal bearing lubricated with three different oils, mineral, sperm, and lard, under loads from 40 to 250 pounds

FIG. 3.



Coefficient of friction of full journal bearing from M.I.T. experiments (Ref. 3); $L/D = 3$, C/D approx. 1/250.

per square inch and at speeds from 300 to 1500 revolutions per minute (Ref. 3).

These experiments were conducted at the Massachusetts Institute of Technology over twenty-five years ago, measuring temperatures with a mercurial thermometer in the bronze bearing, and computing viscosities from Saybolt A readings. The precision obtained is not what might be expected today. Nevertheless the deviations are not systematic. The coefficient depends only on G regardless of the separate values of Z, N, or P; it is unaffected by differences in chemical composition of the oils over the range of variables indicated, and is influenced only slightly by restricting the oil supply to 10

drops per minute. Accordingly Fig. 3 may be considered a practical confirmation of the dimensional theory, and was probably also the first application of the dimensional method in coördinating lubrication data.

At first, when curves were plotted separately for each variable, the problem of finding a general relation connecting them all was found to be a confusing one. But when once it had been discovered by the above analysis that all of the observations with different speeds, loads, temperatures, and different lubricants must be a function of a single variable, a great saving was accomplished in the routine of curve plotting alone. Further, the precision of determining a single curve on the f, G diagram with the aid of all the points is correspondingly greater than the precision of drawing the separate curves, each of which would have to be fixed by a much smaller number of points.

It was found to a first approximation that for large enough values of G, the graph for a full journal bearing is a straight line of the type $f = A + BG$. The occurrence of the constant term, A, seemed anomalous but has since been confirmed by the experiments of Hanocq (Ref. 14) and the McKees (Ref. 15). The linear form of the relation is an empirical characteristic of *full* journal bearings, not a result of dimensional theory. Recent experiments in England (Refs. 13, 16) show that the f, G diagram for *partial* bearings is noticeably curved, being convex upward for a great distance to the right, in accord with Fig. 1. There is a trace of this effect in Fig. 3.

The available data on other performance characteristics such as oil flow (Refs. 12, 16); pressure distribution (Ref. 46 of Section II); and film thickness (Refs. 13, 16) are in reasonable agreement with the simplest results of dimensional theory. The proportionality of load capacity and speed at constant viscosity may be demonstrated in the lecture room with the McKee lubrication indicator.[12]

Whenever a discrepancy appears between experiment and dimensional theory, the probable explanation lies in the omis-

[12] Another very interesting demonstration of dynamical similarity may be made with the ball and slanted tube, confirming the predicted roll time by simultaneous observations on the larger ball and tube, and a reduced scale model (cf. Ref. 11 of Section I).

sion of some essential quantity from the original qualitative equation. In the development of the theory for normal operating conditions it is assumed that no property of the lubricant need be taken into account other than its ordinary viscosity Z. Additional properties are considered below in the discussion of plastic lubricants and thin film lubrication.

THICK FILM LUBRICATION OF GEARS.

Gear performance is customarily expressed in terms of efficiency, and tooth load per unit width, rather than in terms of the coefficient of friction, and load capacity per unit of projected area. Under the special condition of light loads combined with high speeds we may write for the efficiency of geometrically similar gear trains

$$e = F(Z, N, T, D). \tag{32}$$

In (32) e denotes the ratio of the power output to the power input after correcting for such losses as windage, oil churning, and bearing friction; while Z is the effective film viscosity, N the number of revolutions of one of the gears per unit time, T the tooth load per unit width, and D one of the pitch diameters.

Dimensional reasoning converts (32) into the form

$$e = \phi\left(\frac{ZND}{T}\right); \tag{33}$$

which might be further condensed by writing the pitch circle velocity V in place of ND, since the two are proportional. In the same way the minimum film thickness x may be expressed by

$$\frac{x}{D} = \psi\left(\frac{ZND}{T}\right), \tag{34}$$

from which it appears that the load capacity is directly proportional to ZN.

It was found advantageous, in an industrial laboratory, to make the first series of gear tests on a reduced scale model. From (33) and (34) the condition for dynamical similarity is that ZND/T shall be the same for the original and for the model. Hence it was necessary, when using the original

lubricant, to increase the ratio N/T enough to compensate for the decrease in linear dimensions. Under these conditions the efficiency and the relative film thickness would be the same for the model and the original.

Equation (33) shows that the frictional characteristics may be determined by varying any one of the four quantities Z, N, T, or D. This is an illustration of the use of dimensional theory to reduce the number of independent variables. If more than one quantity can be varied a check is available, analogous to that provided in surveying by adding up the angles of a quadrilateral, and equating their sum to four right angles.

THEORY OF PLASTIC AND OTHER NON-NEWTONIAN LUBRICANTS.

Taking the first two terms of Reiner's power series (Ref. 17) as an approximation to the general law of flow of matter, we have for the rate of shear, R, as a function of the shearing stress, S,

$$R = \frac{S - S_0}{A} + \frac{(S - S_0)^3}{B}. \tag{35}$$

In this equation S_0 is the yield shear stress; A is a constant reducing to the ordinary viscosity, Z, when S_0 and $1/B$ are equal to zero; and B is a constant depending on the curvature of the R, S diagram (Fig. 2 of Section I), approaching infinity as the graph straightens out.

Under thick film conditions with a plastic lubricant Eq. (23) will be superseded by

$$f = \phi\left(\frac{S_0}{P}, \frac{AN}{P}, \frac{BN}{P^3}\right). \tag{36}$$

This appears to explain the results obtained with a heavy plastic oil in the M.I.T. experiments cited above. The observarions extended up to G' values of about 10,000, plotting out in the form of a nearly straight line, parallel to the graph in Fig. 3 but located much higher up.

A simple illustration of (36) is obtained by generalizing Petroff's law, Eq. (30), to apply to a plastic solid of the Bingham type, defined by Eq. (35) with $B = \infty$. The derivation is carried through as in Section I except that in place of using

Newton's law we must now take for the viscosity, solving (35) for S/R when $B = \infty$,

$$Z = A + \frac{S_0}{R}. \tag{37}$$

The viscosity of such a lubricant, at constant temperature, is a diminishing function of the rate of shear; approaching the limit $Z = A$ when $R = \infty$. The expression obtained for the coefficient of friction is

$$f = \pi\left(\frac{S_0}{P}\right) + 2\pi^2\left(\frac{D}{C}\right)\frac{AN}{P}. \tag{38}$$

This reduces to Petroff's equation when $S_0 = 0$, since in that event Eq. (37) gives $A = Z$.

THIN FILM LUBRICATION.

A relatively simple condition of thin film lubrication may be defined (Ref. 19) by writing for the coefficient of friction of a journal bearing

$$f = F(Z, N, P, D, a, b, h, k, E_1, E_2), \tag{39}$$

where a and b denote the temperature and pressure coefficients of viscosity; h and k are the heat capacity per unit volume, and thermal conductivity of the lubricant; while E_1 and E_2 represent Young's modulus of elasticity for the journal and bearing, respectively. Eq. (39) is intended to take into account certain phenomena that may occur when the load is progressively increased, but before such effects as wear, seizure, and chemical reactions have taken place to any appreciable extent.

When the film thickness is comparable with the heights of the rough spots, we must be prepared to deal with localized heating and pinching effects, not contemplated under normal operating conditions, and which result in a non-uniform viscosity. If such effects exist, they may be influenced by any or all of the six properties mentioned. Incidentally if the viscosity can no longer be treated as uniform, we must agree upon some definition of Z. This may be taken as the viscosity at the mean temperature of the film, or at the temperature of the bearing surface at a stated point.

It may be asked why no mention is made of the thermal

expansivities of the journal and bearing materials. The *differential* expansions, which may result from temperature *inequalities*, are assumed to be second order effects in comparison with the corresponding differences in viscosity. They should eventually be studied, along with other second order effects such as the temperature and pressure coefficients of a and b. The *major* part of the thermal expansion, as distinguished from the local differences, has, however, already taken place in passing from room temperature up to the steady running temperature at which Z, D, C, and the other quantities are specified.

Looking ahead to Table 2 for the dimensions of the various quantities in terms of force, length, time, and temperature, and measuring all quantities of heat in mechanical units, Eq. (37) indicates that f will be some function of G, bP, h'/P, k'/PND^2, E_1/P, and E_2/E_1; where h' denotes h/a and k' denotes k/a. It is interesting that the three thermal properties a, h, and k have coalesced into two such properties, h' and k'. For any one bearing, D, E_1, and E_2 now being constants, the foregoing reduces to

$$f = \phi\left(ZN, P, b, h', \frac{k'}{N}\right). \tag{40}$$

Thus under thin film conditions ZN/P can no longer be expected to remain intact.[13]

The f, G diagram now shows a branching out effect at low values of G, each component curve corresponding to constant values of the parameters P, b, etc. This may be taken as a proof that some other property of the lubricant (or metal) besides Z is beginning to influence the friction. Such properties are collectively known as *oiliness*.

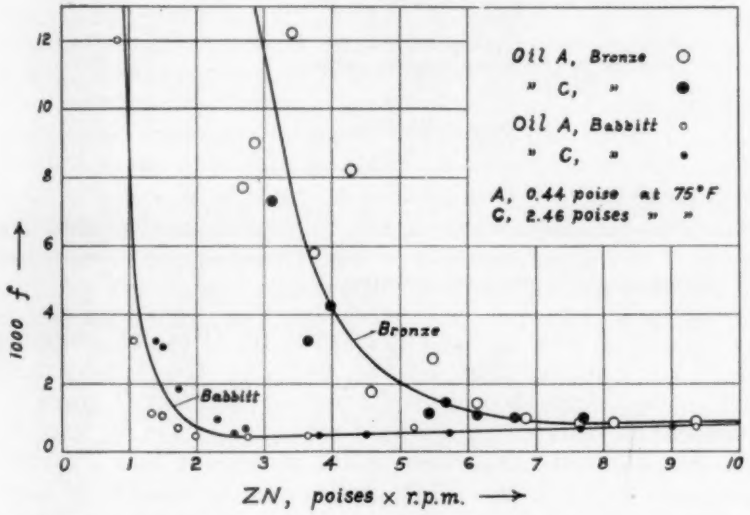
At low enough speeds such that the local heating effects in the film are no longer significant[14] the arguments h' and k'/N drop out, leaving the coefficient of friction as a function of

[13] A statement that f is a function of ZN/P, Pb, $1/P$, etc., would not be incorrect, but conveys no more information than to say it is a function of ZN, P, b, etc., for the reason that any function of three variables x, y, and z is also a function of x/y, yz, and z; or vice versa.

[14] At sufficiently low speeds, a new factor f_0, the coefficient of boundary friction, might have to be included in Eq. (39).

three variables only, ZN, P, and b. Figure 4 from experiments by S. A. and T. R. McKee (Ref. 18) shows the relation obtained when f is plotted against ZN for a constant value of P under thin film conditions. The authors found that all of their results for any one bearing metal, using mineral oils,

FIG. 4.



Coefficient of journal friction with mineral oils, from McKee experiments (Ref. 18) under thin film conditions; $L/D = 1$, C/D approx. 1/1000, $P = 192$ lb./sq. in., temp. approx. 75° F.

could be coördinated with regard to load variations by plotting f against $ZN/\sqrt{P}$. The apparent systematic differences between the two oils in Fig. 4 suggests a possible correlation with the pressure coefficient of viscosity, b.

TEMPERATURE PROBLEMS.

Four fundamental units are sufficient for problems involving temperature, provided heat is measured in work units. Table 2 gives the dimensions of some of the more important thermal quantities in terms of force, F, length, L, time, T, and temperature, Θ.

Buckingham's discussion of the temperature rise in a bearing which has reached thermal equilibrium with its

TABLE 2.

Dimensions of Thermal Quantities.

Symbol.	Quantity.	Dimensions.
C_0	Constant in Newton's law of cooling [15]	$FL/T\Theta$
C_1	Do. for unit area [15]	$F/LT\Theta$
C_2	Do. for Lasche's formula [15]	$F/LT\Theta^{1.3}$
H	Heat per unit time	FL/T
T	Temperature rise, or difference	Θ
a	Temp. coefficient of viscosity	$1/\Theta$
c	Heat capacity per unit volume, metal	$F/L^2\Theta$
h	Do., lubricant	$F/L^2\Theta$
h'	h/a	F/L^2
k	Thermal conductivity of lubricant	$F/T\Theta$
k'	k/a	F/T
α	H per unit area	F/LT
θ	Temperature	Θ
λ	Thermal conductivity of metal	$F/T\Theta$

[15] Heat transfer is considered in Section IV.

surroundings may be cited as an example (Ref. 6), assuming that for geometrically similar bearings the temperature difference T depends only on the journal diameter D, speed N, effective viscosity Z, and thermal conductivity λ of the bearing. His result may be expressed by the statement that T is proportional to ZN^2D^4/λ. This applies only to concentric bearings. To extend the result to heavier loads and lower speeds it is sufficient to multiply by $\phi(G)$, giving

$$T = \frac{ZN^2D^4}{\lambda}\phi(G). \tag{41}$$

As a second example, it may be required to express T as a function of the time t before equilibrium has been reached. Let H denote the power dissipated by friction; and for simplicity assume H is a constant. Then if c is the heat capacity of the metal per unit volume, dimensional reasoning shows that for geometrically similar bearings

$$\frac{\lambda T}{H} = \psi\left(\frac{\lambda t}{cD^2}\right). \tag{42}$$

Observations on one bearing, plotted in terms of these dimensionless variables, might enable us to predict the temperature-

time curve for geometrically similar bearings of a different size D, either larger or smaller, and constructed from different materials. Equation (42) illustrates the principle of physical similarity, thermal rather than dynamical similarity being required. In the model experiment, heat might be generated electrically instead of by friction.

The problem of heat convection due to forced lubrication has been investigated by Boswall and Brierly (Ref. 16), who coördinated their results by the method of dimensions. A more detailed account of temperature problems, taking into consideration heat transfer by convection and radiation as well as by conduction will be found in the next installment.

In conclusion it may be noted that the dimensional treatment consists, in general, of a combination of mathematical and experimental procedure. It provides a partial mathematical solution for problems that are too complicated to be dealt with by the more usual methods of integrating differential equations, as in the case of the load capacity solution for actual bearings subject to side leakage or containing oil grooves. Finally it leads to a definite simplification and economy of experimental work, by reducing the number of independent variables to a minimum.

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THE END OF AN ERA.

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(*Continued from July issue.*)

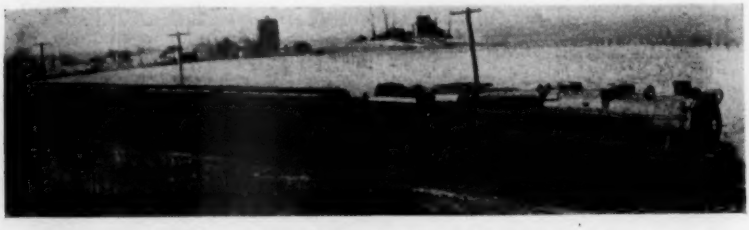
52. The use of the highway for the transport of goods possesses the indisputable advantage of flexibility and, in many instances, it must be patronized before the railway can receive shipments and before the haul is completed. The railway offers speed in transit over long distances. The highway can usually, under present circumstances, perform complete transfer service at lower overall cost within its economic range of distance. The railway is far more reliable, especially under adverse weather conditions. The highway claims lower costs involved in preparing goods for shipment. The railway shows a better record of safety. Just how far each can minimize the advantages held by the other depends upon the vigor and well directed effort with which each problem is attacked.

53. The railway protestation against truck inroads into their l.c.l. freight business, on the basis that the 2.4 per cent. of the total rail tonnage represented by this traffic in 1932 was productive of 10 per cent. of total freight revenues, merits further consideration. The delays which are common with the railway movement detract from the desirability of rail service as viewed by the shippers. The high ratio of expense suffered by the railways renders the business less remunerative than the gross revenue figures would, at first glance, suggest. The solution is obvious. Truck-rail co-ordination must be adopted and can prove profitable to both truck and rail operators. The temporary success of the Alton experience and the encouraging prospects of the newer service just initiated by the Rock Island in transporting loaded trucks and trailers, at a profit to the railway and at a

lower cost than the truck can be operated on the highway, is suggestive of the attitude of the more responsible truck operators who, advised of the actual trucking costs, are willing and eager to coöperate in any coördinated plan which will react to the benefit of both road and rail operations. The fact that such railway services have been well accepted is evidence of the changing attitude of rival carriers who have been struggling to wrest tonnage from parallel lines without regard to the possibility of any coöperative movement, no matter how profitable the most casual survey would show it to be.

54. Of the tonnage which the truck has diverted from the rails, but a very small fraction will be returned by virtue of any improved methods instituted by the railways which do not include the joint service of trucks. The terminal operations represent so vital and costly a part of the transport transaction that, unless the service is predicated upon the cost and convenience to the consumer of transportation, and pick-up and delivery operations organized under the complete transport plan, every avenue being explored to reduce packing costs and loss and damage claims where railway line haul is involved, the truck will continue to successfully solicit the business which the railways seek. In such event, the railway can do no more than attempt to haul the trucks or trailers, subject to acceptance of the service by truck operators, the shipper expressing no choice as to the route or conveyance of his merchandise. It is not difficult to visualize the relatively greater advantage to the railways of dealing directly with the public and they are suffering through the lack of well organized effort. The package car, once filled, is an efficient and fast means for transporting l.c.l. freight between terminals. The fact that it is generally the product of reclassification, requiring not less than five hand trucking operations before package car freight can be consolidated for through movement, reduces the profit to the railway derived from its use. The number of package cars, the loading of which can be completed at the point of origin of the shipments, is limited by the size of the car, and the aim to expedite movement and minimize the number of operations performed is a factor in the unsatisfactory ratio of l.c.l.

tonnage to car capacity in this service. During a recent studied test movement of l.c.l. freight between important cities, situated on the New York Central Railroad where container service is provided, 438 box cars were required to move 2460 tons of l.c.l. freight. During the same period containers attracted 4338 tons which were handled in 381 cars with an average revenue load per car of 11.3 tons as compared with 5.6 tons per car in box cars. The package container lends itself admirably to the extension of the practice of



A train load of merchandise containers on the Pennsylvania.

prompt assembly of merchandise consigned to a single destination.

55. Since the container reduces capacity loads to units of trucking capacity and places packing and crating requirements on the basis fixed by truck handling; since it lends itself readily to unit transfer and unit billing, reducing terminal costs to the level of like expense for carload shipments; since the container has been shown to reduce the empty to loaded mileage ratio; and since goods packed and sealed in containers are more secure against loss due to theft then when carried by either box car or truck, and breaking up the carload into a number of smaller, independent units. one wonders why the practice is not more generally employed as a first step in coördinating road and rail operations in a planned and organized manner.

56. The present handicaps to the extension of container service are, primarily:

1. Lack of any standard in container dimensions
2. The requirement for special cars
3. Limitation of container service to a few railroad systems
4. Costly transfer facilities at terminals

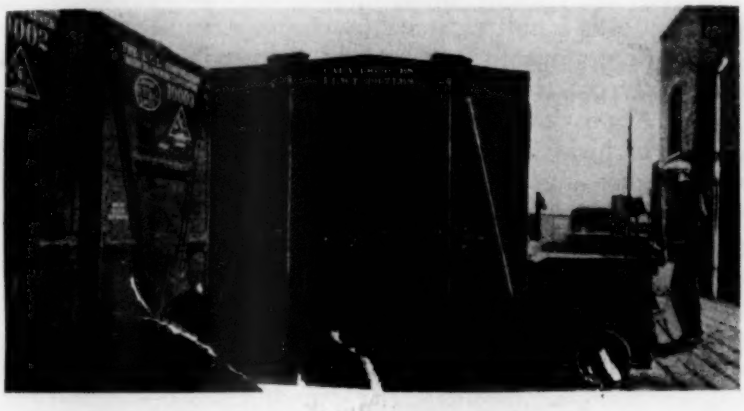
5. Lack of general availability of suitable truck chasses equipped to handle containers

None of these factors appears to offer any insurmountable obstacle. Each could be readily overcome if a serious attempt were made to institute the service on a nationwide basis. Present container dimensions are probably well adapted to meet classes of l.c.l. tonnage offered and might well be standarized, multiples of 2 and 3 in the standard length of container, perhaps, being added to permit interchangeability and the utilization of a single design of container car, thus providing a standard container equivalent of the usual demountable truck body which offers greater cubic capacity, particularly suitable for certain commodities. Such special sizes would not be subject to universal interchange to the same degree that the smaller units would be thus employed.

57. Everyone is familiar with the lack of flexibility experienced and the burden placed upon industry and trade by the lack of interchange of railway freight equipment prior to the adoption of a standard gage for railways and the formulation of an acceptable basis for calculating equipment rentals. Benefitting by that experience and with a precedent established, it should be a simple matter to obtain coöperation of the railways nationally, especially since every record of container operation points to its quick acceptance by shippers, its traffic building possibilities, and its ability to effect large economies where separate billing and handling of many items can be eliminated. Just how much farther economy can be carried by keeping freight cars bearing l.c.l. freight out of congested districts, making property now occupied by costly freight handling facilities available for other purposes, cannot be determined until container service is more widely installed to reduce l.c.l. box car shipments to a minimum. It is likely, however, that with a carefully laid plan in effect for the collection and distribution of merchandise by truck, it will be found economical to locate the rail-truck transfer point well outside the congested area.

58. Both flat cars and gondolas are at present employed for container movement. Recently a special type of gondola has been introduced with drop sides which fall in place in

platform recesses specially provided at a limited number of points. These cars are operated in conjunction with special containers mounted on legs to permit loading and unloading of cars by ordinary lift trucks. While it is a step in the right direction to install simple devices for the simplification of container transfer, special arrangements which co[illegible]e the interchangeability of containers must be avoided [illegible] real progress is to be marked and, unless a general dem[illegible]d is created nationally for such features to recommend the special fitting of all containers, the change should be made in the transfer mechanism in preference to an equivalent modification in the container itself or its carrying car.



59. The section of Transportation Service, reporting to the Federal Coördinator, has analyzed merchandise traffic services, developing the fact that in 1932 the total cost of conducting the service, including a proportion of fixed costs properly apportioned to the traffic, exceeded by 80 million dollars the revenue derived therefrom. In the aggregate, however, the revenue derived from this merchandise traffic exceeded by 107 million dollars the actual out-of-pocket cost and was to that extent profitable. It has been impossible to dispense with facilities and reduce expenses in a measure commensurate with the loss of traffic with the result that, as l.c.l. tonnage falls off, the situation becomes progressively more acute. The Coördinator's recommendations which treat almost entirely with changes in practice, would consoli-

date railway l.c.l., forwarding company, and express operations, establishing a single railway operated agency to perform the various services. Equipment types figure to a very limited extent in the recommendations although mention is made of light weight construction, containers, and demountable truck bodies. It has been shown how the freight container would tend to eliminate the function of the freight forwarding agency since it is apparent that, if the equipment offered by the railways were, in every case, of just sufficient capacity to accommodate each individual shipment, there would be no incentive to assemble the merchandise of various shippers to constitute a load for the type of equipment offered. The container, by breaking up the box car into five or six parts, affords a unit capacity much more readily filled to the point of economical shipment and the need for the extensive and costly practice of repeated reclassification is eliminated.

60. Approximately 75 per cent. of all trucking operations on the highway are carried on over routes of less than 100 miles, according to the report of the U. S. Department of Commerce, as derived from inquiries to which 182 operators, regularly engaged in hauling over fixed routes in 39 states, responded. Forty per cent of all activities are confined to a distance of forty miles. The long haul and coöperland transport of commodities in carload lots still remains with the railways although motor truck operation over distances up to 2500 miles are recorded, the longest hauls being restricted to the movement of household goods. Any changes in methods or equipment contemplated to care for long distance, carload freight are then suggested as means to improve service or lower costs rather than to relieve the competitive situation.

61. In the field of passenger transport, the railways have factors of a very different nature to contend with. Competition is keen and scarcely limited by distance. The private automobile is prepared to go anywhere as long as a well surfaced road is laid for its accommodation. Costs vary but are uniformly low. The infrequent long trip by automobile can justify an assumed low rate in exactly the same way that low rate railway excursions are found to be profitable. The investment is already made, depreciation and interest

charges go on irrespective of any consideration of mileage run. Low railway passenger fares appear inevitable. The ultimate level alone is in question and the all-important question is "How is the most profitable standard passenger fare rate, that is, the rate which provides the greatest net return, to be arrived at?"

62. When a rate, such as 3.6 cents a mile, has firmly established itself over a long period of time, there is a tendency for it to be regarded with a veneration which blinds those concerned to changes in economic conditions bearing upon it. At present, it may be argued that hesitation to experiment with passenger fare rates is justified for, with an economic situation which inclines toward keeping the purchasing power of an apprehensive public throughout the world at a low level, it is impossible to apply, with any great degree of confidence, straightforward economic principles of supply and demand although the present overproduction of passenger transport facilities, represented by over 37,000 available passenger cars with seating capacity for over two million persons, over 22 million automobiles, accommodating nearly 100 million persons, intercity buses capable of seating over one half million persons, affords a potential supply of passenger transportation far in excess of any reasonable prospective utilization of the whole. This fact must depress the rates charged by any common carrier. Moreover, there are so many factors of quantities and values, inexpressible in any definable units, which must be considered, that, to endeavor to set out a formula by which the result of a fare amendment might be estimated, is practically impossible.

63. Such, therefore, is the position which confronts the administration considering the problem of whether or not it should lower its passenger fare rates. How far, it must be decided, for example, should economic theory be modified by the psychological effects of an offer of cheaper fares to a community at present starved of adequate purchasing power, and uncertain of its economic future?

64. The attitudes of the various railways comprising the national system toward low passenger fares are notably conflicting and will be difficult to compromise in view of the economic factors involved. Surveying the country as a

whole, it is observed that, between 1923 and 1930, the railways of the Southern District, as defined by the Interstate Commerce Commission's grouping, suffered the greatest proportionate loss of passenger revenues, and the railways of the Western District suffered more than did those in the East. Another factor which serves to partly explain railway views toward any proposed reduction in basic passenger fares, resides in that part of total revenues accounted for by the transport of passengers. In 1932, the ratio of earnings from passenger carrying operations (as distinct from baggage and mail revenues in the same service) to total passenger and freight transport revenues were:

Southern District	8.3 per cent.
Western District	10.5 per cent.
Eastern District	17.5 per cent.

The railways of the Eastern District, operating 24.3 per cent. of the country's railway mileage, in 1932 produced 60 per cent. of the passenger transport measured in passenger miles.

65. By selecting railways, particularly active in the recommendation of or opposition to reduced passenger fares, and investigating their respective records of passenger revenues and the proportion which these bear to the total for recent years, the justification for the stand which each has taken on this important subject is at once apparent. These data are assembled for several railway systems in the following table:

Railway.	Per Cent. Decline in Pass. Revenues (1923–1930).	Per Cent. of Total Revenue Derived from Pass. Service 1932.	Recommended Basic Fare—Cents/Mile.
N.Y. N.H. & H.	18	38.5	3.6
N.Y.C.	21	29.6	3.6
P.R.R.	30	29.6	3.6
A.C.L.	41	20.5	2.5
S.A.L.	45	16.3	2.0
Southern	49	14.9	1.5
L. & N.	57	13.7	1.5

While repeated conferences of executives of the eastern railways have been held for the purpose of establishing a consolidated attitude toward the threatened necessity for a

reduction of the basic fare on the lines which they operate, no final report has been issued, but they are known to be fundamentally opposed to any such action. Only the vigor with which they are prepared to fight any attempt to enforce lower rates varies in degree with the traffic results indicated, the New Haven, naturally feeling that its interest is best served with the high existing rate. If the four railways of the Eastern District which enjoy the heaviest passenger traffic, the New Haven, New York Central, Pennsylvania, and the Long Island, were to reduce their basic fare from 3.6 cents to 2 cents per passenger mile, it would be necessary for them to attract 180,081,051 passengers per year, based on 1931 traffic averages, a figure within 7½ million passengers of the maximum carried in their banner year 1923, in order to offset the loss in revenue due to the lower rate. At a 2.5 cent rate 144,064,848 passengers would have to be attracted, and, were the rate to be 3.0 cents per mile, the required traffic would be 120,054,041 persons. While these administrations are able to indicate a probable loss of total revenue, other railway systems, less favorably situated to benefit by relatively heavy passenger traffic, advocate and are placing in effect permanent reductions proportional to their respective traffic losses. Thus, the Atlantic Coast Line, suffering a 41 per cent. traffic decline, is prepared to adopt a 2½ cent basic fare. The Seaboard Air Line, recording a 45 per cent. loss from 1923 to 1930, favors a 2 cent fare. The Southern Railway, with a 49 per cent. loss, has experimented with a 1½ cent rate with good success although the railway's first concession anticipated a 2 cent rate which is also favored by the Louisville and Nashville. The Southern Railway's experience in passenger fare reductions has been of particular interest and may well cause apprehension on the part of other administrations. As early as 1929, the Southern experimented with a two cent rate between Macon and Atlanta, extended over a period of 7 ½ months. The 16.98 per cent increase in the number of passengers attracted by the low fare was insufficient to offset the reduced revenue per passenger and the net result of the trial was an 11.19 per cent. decrease in gross revenue. Carrying the experiment further in an attempt to exploit the full potential advantage of low

fares, a 1½ cent rate was placed in effect between certain selected points. The results of this further reduction were most encouraging, a few instances of which are tabulated below:

District.	Period.	Fare.	No. Passengers.	Gross Revenue.
Winston-Salem-Goldsboro	October, 1931	3.6	3,608	$4,109
Winston-Salem-Goldsboro	October, 1932	1.5	11,646	6,539
Winston-Salem-Goldsboro	October, 1933	1.5	18,039	8,023
Ashville-Murphy	October, 1932	3.6	583	600
Ashville-Murphy	October, 1933	1.5	5,355	1,896

Then, reviewing traffic data for the first three months of the system-wide application of the 1½ cent rate with corresponding months of the previous year when the 3.6 cent fare was in effect, the following results are shown:

Increase over previous year—per cent.

Month.	Number of Passengers.	Revenue.
December, 1933	97.47	0.04
January, 1934	109.30	10.75
February, 1934	110.05	18.55

66. A part of this favorable record is, of course, attributable to an improvement in general business conditions within the territory served but it is quite conclusively shown that traffic will patronize the railways providing rates are sufficiently low to make travel by railway, the most economical means of transport. The fact is also developed that there may be a critical median rate, two cents per passenger mile in the case of the District served by the Southern, and that a small reduction below this figure will attract more than a proportionate increase in traffic volume. The rate is startlingly low when judged in its relation to current costs of conducting the service. It is true that, with passenger trains as poorly patronized as they generally are at the present time, a pronounced increase in the number of persons carried could be accommodated with a negligible increase in the cost of conducting the service but, as in the case of the Southern Railway, just cited, the entire increase in gross revenues cannot be transferred into the net income account, a part being absorbed by the added costs involved.

67. But there are other directions in which the unfavorable aspects of railway passenger traffic trends can be modified. A decline in the total volume of traffic offered might be accepted without regret if it were possible to effect economies which would more than compensate for the loss in gross revenues. Nor are railway passenger services judged only by the cost per mile to the patron. Speed, convenience, comfort, frequency of service, and safety are all important and each feature requires careful consideration to the end that every possible means be employed to add to the attractiveness of railway transport which may be introduced, consistent with the cost of producing transportation. Substitute the term, security in transit, for the item, comfort, and the identical factors which define superior passenger accommodations, describe the freight service which will attract traffic. Under the present competitive conditions of operation, it is essential that new standards be adopted, adding to the appeal of the service and that costs be maintained at the absolute minimum. Both equipment types and methods are subject to improvement and the next few years will, undoubtedly, witness more revolutionary changes than have been introduced in all the hundred odd years of the existence of the steam railway.

68. To create traffic, one has to leave all the well-known landmarks behind and travel forth into the unknown. All the mileposts that have served to guide the managements for a century are gone; all the rules that preserved the machine on the rails are now ineffectual. The salesman and his colleague, the administrator, are out on a trackless plain, the one pressing on confident that he knows the way, the other reluctant, unwilling, unbelieving, sure neither of the way nor of his impetuous guide. Since the days when railways were first drawn into the competitive transport market, nothing short of a revolution has been achieved in the conduct of their commercial affairs. Each year has seen its own refinements in practice, and progress has been constantly made. Railway men have suffered from the fact that, until recently, they have always been brought up in an atmosphere of tangible and ponderable considerations. Their training was an education in solids, but the exercise of salesmanship is an exercise in the most gossamer of intangible propositions.

When a man has been brought up in tangibles, his attitude toward intangibles is, to say the least, impatient. The administrator has his feet on the ground; he administers what exists. But the salesman sees visions and dreams dreams; he has to create something that never existed.

69. In the commercial world opportunities are many but they are not always obvious. No system of predetermination exists to point the way to opportunities; they have to be created. Service, facilities, and price all play their respective parts in the display of opportunism by the railway salesman in securing a maximum of traffic to his railway. Allied to this work of sales promotion and, in a measure, resting on it, is the science of business forecasting. One of the most trenchant differences between a public service and a competitive commercial undertaking is that a public service has only to think of what the public wants, while a competitive undertaking has to think of what the public is going to want. It is true that the public can be made to want what is provided, but only within fairly narrow limits. If the public takes a liking to the provided services in general, the impulse to buy can be directed into a particular channel by means of advertising; but if these services are generally unacceptable, the expenditure on propaganda will be too high to make both ends meet. Research is an excellent aid to business forecasting, but intuition is the prime mover. Research provides the material, but the salesman must be, in the end, an inventor. Partly from experience and partly from an accurate understanding of and sympathy with the aspirations, hopes, and circumstances of the passengers in railway trains, and the shippers who originate the tremendous volume of national freight, knowledge is acquired of what will sell and what will prove unacceptable. This business of devising new services is comparable with the devising of new lines of merchandise in the commercial world and is an exercise of the highest faculty the sales manager can command—namely, the creative instinct. Obvious differences obtained between the sales effort required to encourage passenger and freight traffic respectively. So far as the latter is involved, service is being sold to the shipper, whereas in the former case, it is being offered to the general public. It is

the difference between the specialist who sells manufacturing equipment to a newspaper chain and the newspaper which sells to the public. In the one case, the customers can be reached directly by canvassing; in the other case, they cannot. The main channel of sales effort in the interest of freight transportation has, therefore, to be through personal contact. For the promotion of passenger traffic, while much can be done by personal contact, the main channel of sales effort is printer's ink and the medium of the written word or featured displays such as posters, radio broadcasting, exhibitions, moving pictures, etc. Wherever selling is the most important job, then advertising, which is the larger part of selling, is a matter to occupy not the subordinate, but the most competent minds available. Behind the scenes, advertising is a deadly serious business and requires the highest imaginative effort to use it. It is the most intangible, the most imponderable, and the most highly abstract consideration with which a business man has to deal. The human mind, if it be presented with a number of different issues on which it has to reach a decision, will instinctively choose the concrete issues, persuading itself that the abstract issues are less important and can be delegated to a subordinate. Railway officers have had to work out their own plans from first principles. They have had to face competition with a machine that was built for a monopolistic status, but the business man has had to change the emphasis from production to distribution. The change for the railways has been one harder to make, but that for the business man has been harder to realize. The manufacturer has been brought up in an atmosphere that is expressed in Emerson's phrase to the effect that—"if a man excel in the manufacture of an essential service, the world will beat a path to his door." In this respect the manufacturer has had to readjust his ideas to the motto of the present day—"Goods are not bought; they are sold."

70. With full recognition of the merchandising principles which must be respected in the promotion of railway sales of passenger-miles and ton-miles in the new order of things, the typical passenger-mile and ton-mile must be garnished with new refinements and be presented, most likely, with a rewritten price tag. How to construct a finer product

which can be offered at a lower cost has been the problem confronting almost every commercial enterprise in the past decade. Without exception a way has been devised. It is equally essential that the principle be extended to transportation by railway and then, in the broader sense, to completely coördinated transportation.

71. It is interesting to speculate upon the probable distribution of traffic, were an assignment to be effective tomorrow, established on the basis of cost versus service by a single authority judging the merits of each carrier without prejudice, and anticipating the enforcement of the plan which would prohibit the encroachment of railway, highway, pipeline, or air upon the traffic allocated to another. Purely local collection and delivery would, of course, remain the duty of trucks, but the truck deliveries to the railways would probably be less than at present. All l.c.l. freight within a radius of 300 miles might move by truck; it certainly would in all cases where an intermediate railway transfer is involved. Service would be discontinued on many railway branch lines with light traffic. Much local passenger service would be delegated entirely to the automobile. Buses would absorb the balance. The place of the airplane is uncertain. The artificial channel for inland water transport would be abandoned because of its cost. Pipelines would operate at capacity where constructed, and proposed lines. with their complements of pumping and metering stations, would be most carefully scrutinized from the standpoint of cost in its relation to an existing rail line. Whatever form such a program would assume, it is certain that the railways would not derive the volume of traffic, either freight or passenger, which they can most expeditiously or economically handle if given the opportunity to adopt every refinement to speed up rail traffic, eliminate inefficiencies, coördinate transport operations, and reduce costs. Each year marks the introduction of new methods, adopted by the railways as definite progress toward the goal which is no longer obscured by doubt as to what the future holds for transportation. We have witnessed the adoption of store door collection and delivery of goods moving by railways, conducted under the direction of the railways themselves, and at new low costs to the public. The New

England railways have instituted their own air service, extending the practice in effect by other lines which have, for some time, coöperated in a combined rail and air service. Fast, overnight freight trains provide morning deliveries from many points as far distant as 450 miles on many roads. Light weight and corrosion resistance alloys have been cautiously experimented with, their high initial cost preventing more rapid adoption for other than the most exacting requirements. The practice of pooling traffic to avoid duplication of services continues. New railway equipment types appear with striking regularity, the most spectacular and, perhaps the most momentous development in its relation to railway passenger traffic being the light weight, high speed, streamlined, passenger train. From the time of the Union Pacific Railroad Company's announcement of its intention to construct a new and revolutionary type of train to the record-breaking, thousand mile, non-stop run of the Burlington Zephyr between Denver and Chicago at an average speed of 77.5 miles per hour, the attention of the public has been focussed upon railway speeds and it is this feature which they expect to see developed as an aid in holding mass passenger transportation on the rails.

72. Fast, but safe, reliable, and economical travel is the one commodity which railways can offer their patrons to an indisputably higher degree than any rival form of land transport, and although for many years the average rate of travel was not as high as it might have been, there is now little doubt that the lesson of severe competition has proved to the railways that they can make speed a paying proposition.

73. When the overall time of the Twentieth Century Limited and Broadway Limited trains of the New York Central and Pennsylvania Railroads, respectively, were reduced in 1932 from 20 hours to 18 hours between New York and Chicago, the extra fares charged for the use of all of the other important trains operating over these two routes were abolished. In order to make a clear distinction in the relative services afforded, so that the ten dollar surcharge imposed by the Century and the Broadway might be justified, the overall schedules of the non-extra fare trains were fixed at a general level of 21 hours which still gave the service over

this long distance route at an average speed of 45 miles per hour, stops included. The progress of our train accelerations in these days is so rapid, however, that the 21 hour level of schedules is already obsolete. For example, the time of the Golden Arrow of the Pennsylvania has been stepped up to make the run in just over 19 hours; the Manhattan Limited in 19 hours 45 minutes; and the Pennsylvania Limited, newly speeded up by 1 hour 15 minutes eastbound and 25 minutes westbound, in 20 hours. Similar improvements have taken place over the New York Central main line. Last year the Century and the Broadway operated on a new fast schedule to make their through runs in 17 hours 45 minutes each way.

74. The passing years have witnessed progressive speed increases of passenger trains and, for that matter, of freight trains as well, since probably as much as 40 per cent. of all freight traffic in eastern territory moves on 'main trackers,' trains made up at convenient points, contiguous to but not within congested terminals. These trains bear suggestive and picturesque names and, running through to selected terminals on published schedules without stops at any but the most important intermediate points, provide a service superior to any furnished heretofore and one which railways alone are capable of giving. The highest speeds are, of course, regularly operated in passenger service and, while speeds of 90 and 95 miles per hour are not infrequently attained by trains of conventional type over stretches of track where conditions are favorable to operation at such speeds, it is still difficult, in view of the many restrictions imposed by grades and curvature, to obtain mile-a-minute schedule speeds. Then too, costs rise rapidly with speed, both as the result of added resistance which must be overcome and due to the expense involved in maintaining both rolling equipment and right of way in such a state approaching perfection as to make high speeds safe and comfortable.

75. Until most recent years, transportation engineers have not been generally conscious of the magnitude of forces imposed by the atmosphere upon bodies passing through it at high speed. The reason for their apparent lack of appreciation resides in the fact that, until airplanes increased the transport speed range and invaded a medium which

offered no resistance other than that due to disturbances of the air mass and the friction acting between air and vehicle surface, air resistance accounted for a relatively small part of the total power requirements. With a modern, ten car passenger train, air resistance consumes less than ten per cent. of the total resistance encountered at thirty miles per hour. Increase the speed to sixty miles per hour and air resistance represents approximately twenty-five per cent. of the total whereas, if the speed is further increased to one hundred miles per hour, approximately forty-five per cent. of all the force exerted by the locomotive, and forty-five per cent. of the fuel consumed, are required to part the air, overcome its drag on exposed surfaces, set up the many turbulent eddies which form wherever the air mass is violently disturbed by the presence of a jutting projection, and to maintain the zones of alternate high and low pressure which surround each fast moving body. This train is moving in quiet air. Introduce a head wind, the velocity of which adds to that of the moving train in the calculation of the force exerted by the air, a side wind which causes the flanges of the wheels to bear heavily on one rail, or a quartering wind which offers a component to produce both effects simultaneously, and resistance is increased in proportion.

76. It is not because the presence of air resistance has been unknown that measures have not been taken to restrict its effect in opposing the movement of railway trains. High speeds were realized and still higher speeds anticipated in the very early days of railroading. Writing in his diary which has been carefully preserved, Charles C. F. Greville, nephew of the Duke of Portland and Clerk of the Council to King George IV, in 1834 chronicled the ambitious accomplishments and prophesies of men of the period—

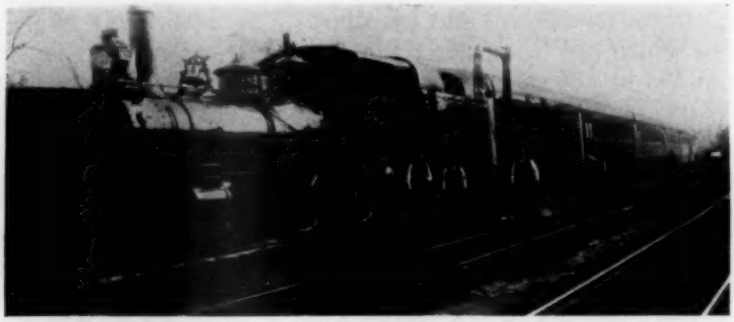
"I heard wonderful things of railroads and steam when I was in Staffordshire, yet by the time anybody reads what I now write, how they will smile perhaps at what I gape and stare at, and call wonderful, with such accelerated velocity do we move on. Stephenson, the great engineer, told Lichfield that he had travelled on the Manchester and Liverpool railroad for many miles at the rate of a mile a minute, that his doubt was not how fast his engines could be made to go,

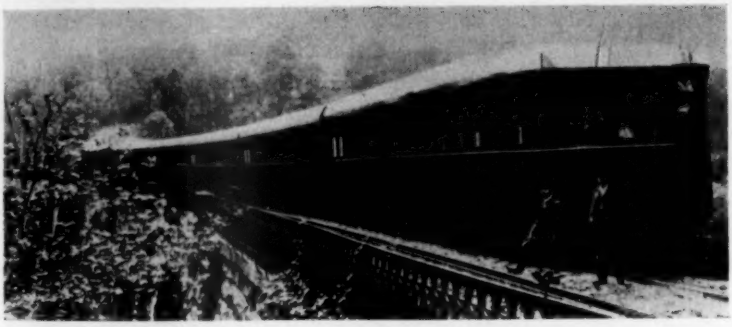
but at what pace it would be proper to stop, that he could make them travel with greater speed than any bird can cleave the air, and that he had ascertained that 400 miles an hour was the extreme velocity which the human frame could endure, at which it could move and exist."

In 1847, Sir Henry Bessemer investigated the air resistance of railway vehicles but his work was not completed owing to a general lack of interest in this subject which had not yet developed sufficient importance to claim the attention of those concerned with the design of railway equipment.

77. The first known record of the application of streamlining principles to equipment operating on American railways is that of the experimental Baltimore and Ohio train upon which tests were conducted in the summer of 1900. The design was that recommended by Frederick U. Adams, whose attention was first directed toward the importance of air resistance when reading of the construction conceived by an inventor who proposed a locomotive, propelled by a single, sixteen foot driving wheel and supposedly capable of unprecedented speeds. Later, Mr. Adams developed a plan for an unbroken side structure for railway coaches, adopting vestibule construction and carrying the shrouded sides nearly to the rails. The design, described in his book published in 1892, was experimentally adopted, producing the test train of the Baltimore and Ohio Railroad, illustrated on the following page. The results of investigations dealing with the resistance offered by this train were disappointing when compared with the performance of conventional trains of the period due, undoubtedly, to the facts that maximum speeds scarcely exceeded sixty miles per hour and the equivalent cross sectional area of standard coaches was increased by the construction as was the surface area exposed to the frictional drag of the atmosphere and cross winds, conditions which served to offset any advantage gained by eliminating some of the eddies otherwise existent about car sides. In spite of the fact that dynamometer tests conducted upon a train of conventional design and one employing the Adams construction indicated a slight increase in power requirements as a result of the streamlining efforts, the principles laid down at that time have since been proven basically sound and have

been utilized to advantage in recent railway construction, notably in the design of the new series of high speed, light weight, streamlined trains inaugurated by the Union Pacific and Burlington railways. Limitations imposed by the necessity for adapting the Adams streamlining principle to existing railway equipment of 1900, and the failure to employ recommended modifications upon the locomotive, account for the ill success of the inventor's demonstration.





78. The study of streamlining was renewed and research in this direction was attacked with new vigor with the introduction of air travel. The principles have now been established with certainty and the fuselage of the modern airplane is given a form closely approximating that which minimum resistance dictates. Streamlining of land vehicles presents a more difficult problem. The effect of running on wheels with the body close to the ground complicates the forces with which the engineer must deal and creates a condition which

renders impossible compliance with all the fundamental laws of aerodynamics. The railways are fortunate in having at their command, as they embark upon the study of streamlined railway shapes, all the mass of data which the aeronautical industry has been able to assemble and the facilities for testing the properties of various forms which have been developed as aeronautics required their use. As a result of this progress, the first serious attempt to produce scientifically correct contours for railway vehicles, as exemplified by the two trains mentioned and by other trains of the same general type which are being placed in service as rapidly as the economic study of their capabilities will warrant, has met with remarkable success. Of no less importance than the knowledge of the principles of streamlining are other features, products of modern research, many of which were developed independently of railway needs. These have been combined in the construction of these newest trains. New, light weight, corrosion resistant metals and alloys are now commercially available and the internal combustion engine has added measurably to the success of these initial attempts in providing a superior service to the public at a lower cost to the railways than any acceptable form of railway unit has ever heretofore been capable of affording.

79. As the expenditure for fuel in hauling a ton of weight is the same whether or not it is paying load, it is evident that the smaller the percentage of total weight moved represented by non-paying or dead weight, the lower will be the cost of hauling revenue tonnage. While it cannot be truthfully said that the railways have been blind to this obvious fact, one cannot view modern railway equipment without being impressed by the relatively low net to gross weight ratio afforded by equipment types in all classes of service. The evolution of railway cars, in both freight and passenger service, respects many time honored experience factors. The progressive addition of each pound of weight has been the result of carefully studied investigation and justified in the interest of safety, dependability, moderate maintenance, car life, or riding qualities. Open hearth steel and riveted construction have been patronized because of the lack of availability of better materials, offered at costs which were not prohibitive,

and of proven fabricating practices demonstrating superiority. Weight will always contribute to the excellence of riding qualities, particularly spring supported weight in its relation to that part constituting wheels, axles, journal boxes, and equalizers which are unsprung. Improved cushioning elements and the introduction of rubber inserts to absorb high frequency vibrations and to insulate metallic contact have gone far to make practicable weight reduction in passenger carrying cars. Comparable progress has been witnessed in freight equipment with the present trend toward non-harmonic spring groups and friction elements to dampen recoil. When ordinary grades of steel are used in car construction, fabrication by welding promises well to largely supplant riveted joints in the interest of weight reduction.

80. Maximum economy in car weight introduces additional car cost. Experience with both freight and passenger designs has shown that more moderate weight saving can be effected without such penalty simply by taking advantage of modern methods and refinements in design. As an illustration of what is being accomplished in this direction, we may well pause to consider three car types of the same general classification, all being 50 ton single sheathed box cars, recently tested by the American Railway Association to determine their relative durability under extreme impact conditions. Specifications of particular interest in this connection are given below.

Design.	Design Date.	Light Weight—lbs.
U.S.R.A.	1919	47,600
A.R.A. Tentative	1923	47,000
A.R.A. Standard	1932	44,000

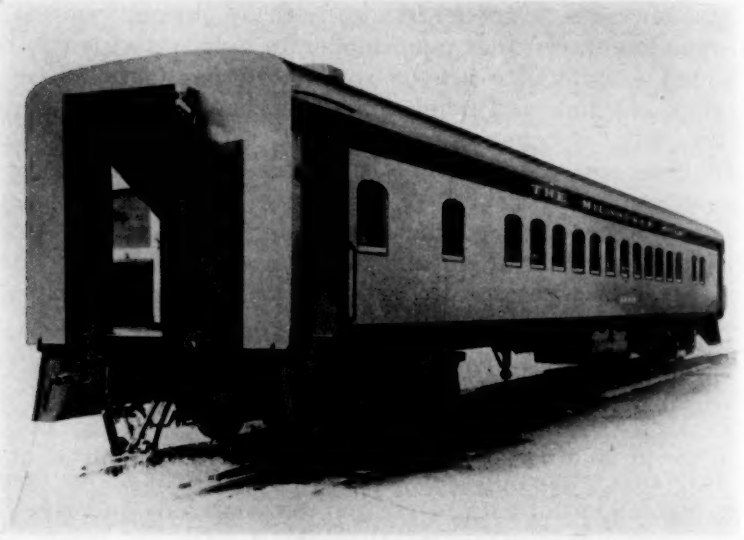
81. It is important to realize that each of the above three car types was built up of comparable materials and riveted construction was employed throughout with the exception of the center sill of the standard A.R.A. design which uses a fabricated section with welded seam.

82. These cars were successively subjected to identical trial conditions, the results of which point to the superiority of the A.R.A. standard design. Quoting item (*e*) from the report of the tests, it is stated,

"Considering the performance of each unit of equipment

as a whole, the A.R.A. standard cars demonstrated their capacity to absorb abnormal collision punishment under full axle load without damage of consequence, whereas both the U.S.R.A. and tentative A.R.A. carbody structures showed unmistakable evidence of approaching failure."

83. Such results are a tribute to railway research and are indicative of the progress which is being witnessed in the railway attempt to solve its problem of reducing the cost of producing transportation to keep pace with new demands. Of particular interest is the fact that the standard A.R.A. car, while exhibiting superior service strength and a three thousand pound reduction in weight as compared with the A.R.A. tentative design, can be produced at an estimated saving in cost of approximately sixty dollars per car.



84. Another striking evidence of the prompt response of the railways to new methods, immediately upon proof of their adaptability to car construction, is observed in the new passenger car equipment, welded throughout, the first units of which have already been installed by the Chicago, Milwaukee, St. Paul and Pacific Railroad. The first trial coach of this series, No. 4000, was a rebuilt standard unit. The

original riveted steel underframe was retained and an all-welded steel body replaced the familiar riveted construction. A notably successful design resulted and a second unit was built, No. 4400, welded throughout and representing the basic design upon which fifty additional units will be fabricated. The original coach design, employing riveted construction but offering identical overall dimensions, weighed 146,000 pounds. Coach No. 4400, illustrated above, weighs 96,000 pounds, representing a saving in weight of 34.2 per cent. To make these coaches, which are to be used in day and night through service between Chicago and the Pacific Coast, particularly attractive, the space per passenger has been increased from 6.5 to 10.5 square feet, reducing the seating capacity from 78 to 54, offset in part by the provision of adjustable, reclining back seats which eliminates the necessity for each passenger to require two double seats for comfort in night travel. Progress in passenger car construction is also reflected in the provision of forced air circulation for ventilation and car heating with a view toward later installing air conditioning equipment, sound proof insulation, automotive type, wide windows, attractive interior finish, and rubber insulated, ball bearing mounted trucks of special alloy cast steel for light weight.

85. When reduction in weight is accompanied by an increase in car cost, particularly in freight service where no traffic stimulating factors are involved and either the heavy or light design will serve the shipper equally well, the economics of weight reduction need be most carefully investigated since every element of freight car cost may be intimately affected. Since the load capacity of every car is limited by the size of the axle journals employed, any decrease in the dead weight of the car immediately adds to its potential load carrying capacity of which the operating railway may take advantage without exceeding the specified loading of the standard journal. This benefit, of course, can only be realized in the case of freight cars, such as open top types, which, when under load, invariably carry maximum tonnage. Added load capacity, obtained by weight reduction, is primarily the peculiar advantage of the high capacity car which has become more and more popular as the railways have

adapted their equipment and operating practices to the requirements of mass transportation.

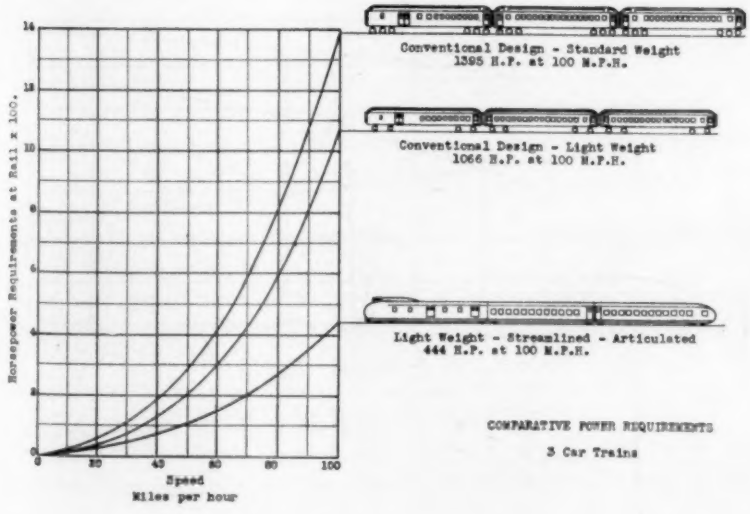
86. Whether or not any railway can afford to adopt a higher capacity car depends upon the number of cars required to satisfy the needs of its patrons. In 1920, the Interstate Commerce Commission reports 2,350 707 freight cars, including 933,129 coal cars in service. By 1930, these had been reduced 1.9 and 2.6 per cent. to 2,305,741 and 908,245 cars, respectively. In the same period, average freight train speed increased 34 per cent. from 10.3 to 13.8 miles per hour and the number of times each active car was loaded per year increased 26.1 per cent. Assuming just sufficient number of cars of present capacity on the line to satisfy the needs of the service, it is questionable whether or not the service could be accelerated to the required extent to permit a reduction in this number of cars by any ratio governed by a proposed increase in car capacity, the aggregate capacity remaining unchanged.

87. The benefits to be derived from the use of light weight freight car equipment are reflected in innumerable directions and, while every practical consideration points to the actual existence of a potential saving in each account, it is often difficult to translate the less obvious advantages into terms of dollars and cents. Furthermore, operating conditions differ throughout a broad range with the result that local variations in practices and the nature of the traffic handled require consideration so that the effect of car dead weight must be separately developed by any railway which contemplates the purchase of new equipment, applying cost factors as they obtain in the territory served.

88. That locomotive fuel and water costs will respond to any decrease in the weight of equipment is perfectly obvious. When the load capacity of freight cars is fully utilized, any increase in maximum capacity will result in fewer cars required to handle a given amount of net tonnage, fewer trains, and consequently lower costs in all accounts which vary with car miles and train miles. Fewer cars to be handled in turn reduce the yard expense involved in car classification. There is an indeterminate economy in the cost of track and bridge maintenance as lighter or fewer cars are moved.

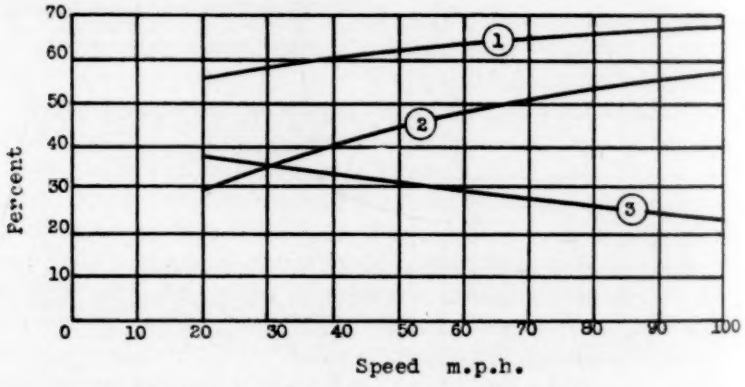
Opposed to all of these separate avenues of saving there is the element of fixed charges to be considered. These increase with added equipment cost. The problem is complex but not incapable of studied analysis when data are available to indicate unit costs as they obtain in each type of service in which any proposed car design will move. Without recourse to such investigation, no railway administration is in a position to intelligently appraise the relative advantages of improved equipment types.

89. When speeds are moderate and the line involves grades which limit the trainload, weight reduction is a vitally important consideration. On the other hand, when very high speeds are contemplated, as in some fast passenger services, and especially if a low grade line is involved, streamlining may be relatively more important. The combined effect of light weight and streamlining is shown in the diagram on the following page to reduce the power requirements for a three car passenger train by no less than 68 per cent. at 100 miles per hour, while light weight alone, anticipating a 14.3 per cent. decrease in sectional area, accounts for a saving of approximately 23.5 per cent. The units here considered are; first, a three car, multiple unit train of conventional weight and design; second, a three car multiple unit train of con-

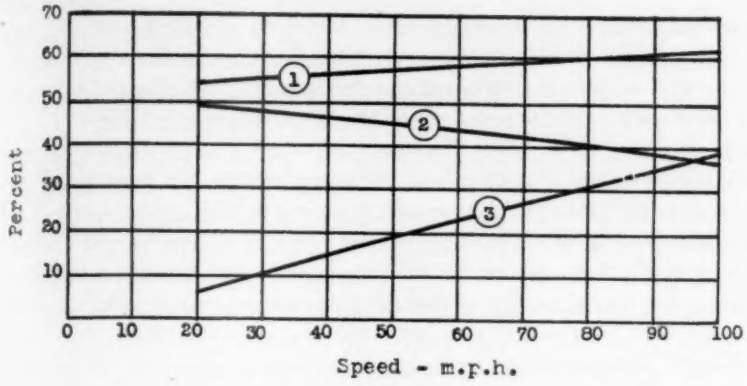

Horsepower Requirements at Rail x 100.
Speed
Miles per hour
Conventional Design - Standard Weight
1395 H.P. at 100 M.P.H.
Conventional Design - Light Weight
1066 H.P. at 100 M.P.H.
Light Weight - Streamlined - Articulated
444 H.P. at 100 M.P.H.
COMPARATIVE POWER REQUIREMENTS
3 Car Trains

ventional design but with its weight reduced 52.4 per cent; third, a light weight, streamlined, articulated train of the same weight as the second train but with its cross sectional area reduced 26.1 per cent. below that of the first train.

90. On level track, the proportionate effect of weight reduction decreases steadily as speed increases. The opposite effect is observed in the case of streamlining. This condition is graphically illustrated on the opposite page. Introduce a moderate grade and the relative influence of weight reduction and streamlining are transposed at high speed. On an ascending one per cent. grade, an additional unit resistance of twenty pounds per ton of train weight is added to that represented by inherent train resistances and, under certain conditions, this becomes the predominating influence restricting maximum speed. According to the above values, derived in Appendix *A*, whereas a saving of 23.5 per cent. is credited to weight reduction and 53 per cent. to streamlining at 100 miles per hour. the succeeding chart shows that, on a one per cent. ascending grade, weight reduction accounts for a saving in power of nearly 40 per cent. while the effect of streamlining conserves scarcely 35 per cent. of the power otherwise required. So it is that conditions under which any proposed construction is to be operated must, in every case, be carefully analyzed to direct design in the interest of



Percentage of saving in horsepower on level tangent track.
(1) Saving realized on substitution of light-weight and streamlined design for conventional construction.
(2) Saving realized by streamlining.
(3) Saving realized by weight reduction.



Percentage of saving in horsepower on a 1.0 per cent. ascending grade.
(1) Saving realized by substitution of light-weight and streamlined design for conventional construction.
(2) Saving realized by streamlining.
(3) Saving realized by weight reduction.

the most profitable train type. Very definite conclusions may be drawn from a study of this nature with respect to the features of construction to be accorded particular attention in various typical services.

(1) Trains which are to be operated at very high speeds over long distances should be given a highly developed streamline form and reduction in weight should be accorded equal consideration.

(2) For high speed trains, operating between important terminals in heavy traffic territory without intermediate stops, and on a low grade line, particular attention should be directed toward streamlining.

(3) When more moderate speeds are anticipated and heavy grades must be contended with, or when fast schedules are required with frequent stops as in suburban commutation service, weight reduction should positively govern design.

In every case, the relative cost of conducting the service, employing various equipment types, must be considered in its relation to the commercial factors introduced by reason of competition or changing standards of accommodation required in the interest of traffic volume.

91. The internal combustion engine, which has been the element responsible for the railways' greatest traffic loss, has

also proven to be an important ally in its adaptation to the power requirements of the very trains with which the railways hope and expect to regain some measure of their lost revenues. It promotes light weight since the internal combustion engine is compact and requires no essential complement of a separate tender to carry a bulky fuel, or water to be consumed in the process of power development. Streamlining presents no serious problem when the power unit is contained within a car body. Speed can be economically and safely advanced since, by eliminating reciprocating parts from any driving wheel attachment, it is possible to use wheels which are balanced both statically and dynamically, thereby relieving the track structure and bridges of the "hammer blow" characteristic of the conventional steam locomotive. The internal combustion engine also lends itself to a type of mounting which locates the engine low in the car structure, reducing the height of the center of gravity and permitting proportionately higher safe speeds on curves. The low engine speed of the Diesel type engine and the fact that it burns a low cost fuel of low volatility especially recommends its use in railway service.

92. Insofar as capacity of the power plant at speed is concerned, the internal combustion engine can claim no inherent advantage over steam. Its higher thermal efficiency will, however, reduce the weight of fuel which must be carried and water for steam generation purposes will always prove burdensome until some compact and practical system for a condensing system with return to the boiler is developed. The electric transmission, a necessary adjunct to the internal combustion engine for heavy duty railway service, is both heavy and costly. A suitable steam power plant will eliminate this. While an entirely satisfactory steam power plant may be developed for very high speed service, it will undoubtedly assume a form quite different from that of the conventional steam locomotive although, at the present time, the Baltimore and Ohio Railroad is experimenting with a steam locomotive of basically conventional pattern and European engineers are engaged in a number of similar projects. The Baltimore and Ohio high speed locomotive will embody many refinements in design among which are num-

bered streamlining, a water tube fire box and high pressure boiler, and it will be designed for use in hauling a light weight, streamlined train of the most modern type.

93. The introduction of the diesel-electric unit for railway motive power has brought with it a method of capacity rating which, common in other fields, is new in railway work. In the past, it has been the practice of locomotive builders and railway mechanical officers to define the capacity of any locomotive type in terms of tractive power or tractive force, a unit which, expressed in pounds, is a measure of the propelling force exerted at the rim of the driving wheels by the action of the steam against the piston and thence, through the rods and wheel centres, to the rails. The common expression for tractive effort takes the form:

$$TE = \frac{\frac{1}{2}pd^2s}{D},$$

where TE = tractive effort expressed in pounds,
p = mean effective cylinder pressure in pounds per square inch,
d = diameter of piston—in inches,
s = length of piston stroke—in inches,
D = diameter of driving wheels—in inches.

Owing to the pressure drop which occurs between boiler and cylinders, the value of the mean effective pressure is always some amount less than actual boiler pressure and since the values for boiler pressure is more readily obtainable, tractive effort has been more popularly expressed as

$$TE = \frac{0.85\,Pd^2s}{D},$$

where P = boiler pressure in pounds per square inch.

94. By the use of this formula, capacity characteristics of steam locomotives at starting and low speeds, were, for many years, quite accurately expressed. With constant refinement in locomotive design, however, and with the progressive addition of auxiliary devices to improve efficiency, the loss in pressure suffered between boiler and cylinders became less pronounced at long cut-offs but more variable,

resulting in the substitution of the formula,

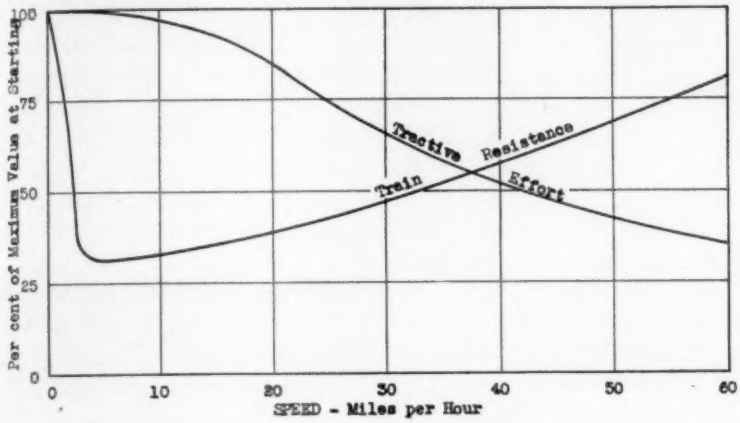
$$TE = \frac{0.93\ Pd^2s}{D},$$

when steam locomotives of the most modern type are considered.

95. All of the above expressions for tractive effort are valid only throughout the short period during which locomotives operate at maximum cut-off (cylinders communicated to the boiler through the valves during the greatest possible proportion of the piston travel). As speed increases and communication between boiler and cylinders occurs more rapidly, the point is soon reached at which the steam generating capacity of the boiler can no longer supply the more rapidly recurring demands of the cylinders for steam. It is then necessary to limit the time during each piston movement that the steam passage is open between boiler and cylinders. As this is accomplished, mean effective pressure assumes a lower value and the tractive effort at the rails becomes progressively less. Then, to define tractive effort at any speed, there are introduced "speed factors," constant values corresponding to various piston speeds which, when multiplied by the rated tractive effort at starting, define locomotive capacity at various speeds of travelling. The speed factors suitable for use with modern road locomotives are uniformly higher, throughout the entire speed range, than those applicable to the older locomotive types. This is for the reason that the modern locomotive is fitted with a boiler of greater steam generating capacity than that employed with earlier types, thus permitting higher steam consumption in the locomotive cylinders at all speeds and a longer cut-off at each speed.

96. Maximum tractive effort at starting and at very low speeds has served for many years as a practicable and reasonably accurate measure of locomotive capacity since, like tractive effort, the magnitude of the resistances to be overcome also assumes a high value at starting and decreases rapidly until it assumes minimum proportions at a speed of approximately five miles per hour, rising gradually as speed increases. In the accompanying diagram is shown the

characteristic tractive effort curve of a locomotive of the older type. The variation of train resistance with speed is also indicated. It is here shown that the typical steam locomotive which exhibits the stated characteristics, is capable of



accelerating its train on straight, level track up to a speed of approximately 38 miles per hour at which point train resistances balance tractive effort and the locomotive is just capable of maintaining this constant speed with any train which it can start and haul at very low speed. Since the curves represent typical values obtaining in freight service, it is shown that, as long as freight train speeds did not exceed forty miles per hour, tractive effort at starting was a suitable measure of capacity for the older locomotive types and, since the speed factors of modern steam locomotive assume higher values than observed for older designs, tractive effort is better maintained at speed and the value of the tractive effort unit is automatically carried over into the more modern series.

97. The capacity of all internal combustion engines is more advantageously stated in terms of horsepower, a unit which introduces into its definition the element of speed, its relation to tractive effort being expressed by the equation:

$$HP = \frac{TE \times V}{375},$$

where HP = horsepower,
TE = tractive effort in pounds,
V = speed in miles per hour.

The inherent characteristics of the reciprocating steam locomotive are such that maximum horsepower is developed within a very narrow speed range whereas the diesel powered unit with electric transmission maintains nearly constant horsepower output from low speed to any practical maximum speed for which it may be designed. Thus it is that, by stating the horsepower of the diesel-electric unit, its ability is well defined whereas, in the case of the steam locomotive, a statement of its maximum horsepower is meaningless unless associated with the speed at which the stated horsepower value is obtained. Moreover, the horsepower curve of the steam locomotive may assume a variety of forms and, given the maximum horsepower of any design, its adaptability to any peculiar service condition is unknown unless properly supplemented by further data. Again, a steam locomotive may be operated for an indefinitely long period at any tractive effort-speed combination obtainable whereas, within the lower speed ranges where maximum tractive effort may be delivered, the period of operation of the diesel unit with electric transmission is strictly limited by the capacity of the electrical apparatus to carry the heavy current required. Operation at capacity and at such low speeds for an extended period, exceeding the specified time rating, will result in damage to the electric motors. Consequently, maximum tractive effort rating for diesel-electric units could not be assigned the same significance as is accorded a similar statement of steam locomotive capacity and the deviation from prior railway practices in this respect is readily understandable.

98. High schedule speed is more than a matter of power plant capacity and the ability to accelerate a train rapidly at ordinary balancing speeds. Maximum speeds, operated over short distances, can never prove very effective in shortening terminal to terminal time. It is more important that a more moderate speed be maintained continuously over long stretches of track and, by operating in this manner, the total fuel cost for the run can be limited to the lowest possible, consistent with the service given. A uniform and high aver-

age speed calls for high speeds on curves, high acceleration and deceleration rates, and a minimum number of speed restrictions imposed. Light weight is important. It has already been demonstrated that light weight is practicable and not difficult to realize. Since curvature cannot be eliminated and can be modified only by expending huge sums to improve alignment, not much progress can be looked for in this direction. Slower trains will be required to share the rails with the newer line of passenger equipment and their operation would suffer were superelevation on curves to be increased to the point that very fast schedules would not be interfered with unless the new trains were accorded structural considerations looking toward lower centres of gravity to increase their safe speed on curves of less than the ideal superelevation. It is this factor which strictly limits the adaptability of the conventional locomotive, both steam and electric, for high speed service. The most modern electric passenger locomotive carries its centre of gravity seventy inches above the rails. Steam locomotives, with heavy, water-filled boilers set clear of large diameter driving wheels, are still greater offenders in this respect. The centre of gravity over the leading truck of the Burlington Zephyr is but 52.5 inches above the rails although the engine is mounted over this truck. Had the engine been mounted on a depressed bed between trucks, a type of construction common to several subsequent designs, it is probable that even this low figure would have been improved. The highest centre of gravity in any passenger train length invariably occurs at the power unit. Light weight car design automatically lowers the concentrated weight below the height experienced with standard heavy cars and even heavy cars can safely negotiate curves at speeds higher than those on which the locomotive which hauls them can safely travel. From the standpoint of safely maintaining speed on other than tangent track, then, there is little to be gained by reducing the weight of car equipment and retaining the steam locomotive of standard pattern. It is difficult to see in what manner steam power can compete with the internal combustion engine for maximum high speed service unless quite revolutionary developments are witnessed in its construction. That these are in prospect is evidenced

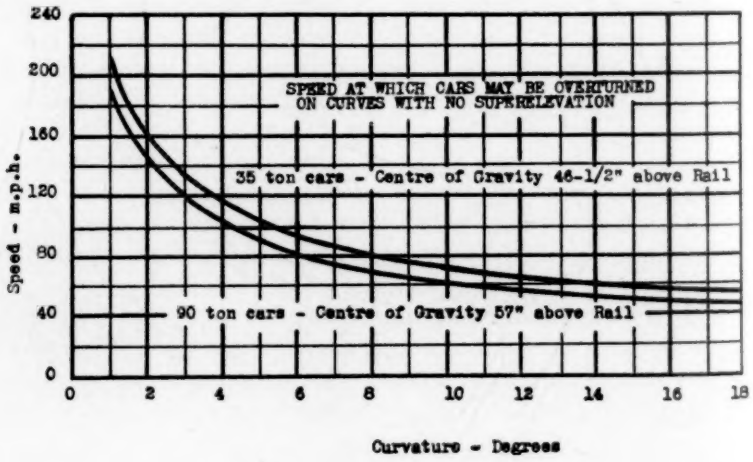
by new designs, already prepared, of turbo-electric locomotives anticipating efficient steam units capable of bettering the performance of the finest modern steam locomotives in use today which employ the reciprocating principle.

99. The maximum speed at which any unit of railway equipment can be operated upon curved track without superelevation may be theoretically derived by equating the moments which respectively tend to overturn and to maintain the car on the rails. The basic equation defining this speed is

$$V^2 = \frac{2{,}415{,}768}{Ch},$$

where V = critical speed in miles per hour,
C = degree of track curvature,
h = height of center of gravity above the rails.

There is thus indicated the fact that the critical speed is not influenced directly by the weight of the car but is dependent only upon the radius of the curve and the height of the centre of gravity. Investigating, in this manner, the relative safe speeds of typical cars weighing 35 and 90 tons, with centres of gravity 46.5 and 57 inches respectively above the rails, it is demonstrated, as disclosed by the following chart, that the light car may traverse a five degree curve without overturning at 100 miles per hour, whereas the heavier car is limited to curvature not exceeding four degrees.



100. A simple analysis such as the above is of no practical value in determining safe speed on curves but can be used only as a means of examining the relative stability of railway equipment. Actually, the safe speed is modified by super-elevation of the outer rail, inevitable slight irregularities in track surface, side winds, and the tendency for an unbalanced lateral force to depress the springs on the side toward which it acts, thus causing the displacement of the car body transversely of the rails, aggravating any existing condition of unbalance.

(To be Concluded)

The Quadrature Oscillograph.—(*Power Plant Engineering*, Vol. XXXIX, No. 7.) JESSE B. SHERMAN, in a paper in the Proceedings of the Institute of Radio Engineers, describes this apparatus which overcomes the difficulty in the use of the conventional mechanical oscillograph with variable speed mirror for observation of phenomena not of constant frequency. A mechanical galvanometer giving quadrature deflections in addition, provides means for producing Lissajous figures, hysteresis and other loss loops, and other two coördinate figures. This is in effect a low frequency substitute for the cathode ray tube.

The direct projection method of the Einthoven galvanometer is employed, using longitudinally bored poles and optical magnification by means of a projecting microscope. However, instead of projecting the shadow image of a vibrating string, a slitted mask mounted on parallel strings permits restricted passage of light. Two slitted masks, one on each vibrator with their planes parallel to each other and with their slits at right angles will produce on the screen a square spot of light resulting from the intersection of the two slits. If either vibrator alone moves under the application of an alternating E.M.F. a bright line will be traced on the screen. The movement of both vibrators will result in the production of Lissajous figures precisely as in other cases of quadrature vibrations.

R. H. O.

MEDAL DAY MEETING.

The annual Medal Day Meeting of The Franklin Institute was held in the Hall of the Institute at three-thirty o'clock on the afternoon of Wednesday, May 15, 1935.

This meeting, which was also the regular monthly gathering, was called to order by the President, Mr. Nathan Hayward.

Upon motion, the minutes of the preceding meeting were approved as printed in the JOURNAL OF THE FRANKLIN INSTITUTE.

The next order of business to come before the meeting was the presentation of awards and Certificates of Honorary Membership. At this meeting all the recommendations made by the Committee on Science and the Arts during the past year were brought to a conclusion by the presentation of the individual awards.

An innovation in the programme this year was the addition of music. Mr. Guy Marriner, Musical Adviser to the Director, was at the piano accompanied by two members of the Philadelphia Orchestra. The programme was opened by the selection "Andante and Allegro from Opus 2" by Handel.

PRESENTATION OF CERTIFICATE OF MERIT.

To Mr. George S. Kelley, New York City. Dr. Joseph S. Hepburn, sponsor.

The President called upon Dr. Hepburn.

Dr. Hepburn: "I have the honor to present to you, Mr. George S. Kelley to receive a Certificate of Merit 'in consideration of the invention of an apparatus for the removing of dust produced in the drilling of rock and the resulting lessening of the silicosis.'"

The President presented the Certificate as follows: "Mr. Kelley, I present to you a Certificate of Merit for your work in reducing that most dread occupational disease 'Silicosis.'"

Mr. Kelley expressed his thanks for this award.

AWARD OF LONGSTRETH MEDALS.

To Mr. Edmond Bruce, Red Bank, New Jersey. Mr. Coleman Sellers 3rd, sponsor.

The President called upon Mr. Sellers.

Mr. Sellers: "Mr. President, it is my privilege to sponsor Mr. Edmond Bruce of the Bell Telephone Laboratories of Red Bank, New Jersey, who is to receive an Edward Longstreth Medal 'in consideration of his design and development of antennæ for short wave communication combining superior efficiency, high directivity, simple construction, and effectiveness over a broad range of frequencies.'"

The President presented the Medal as follows: "Mr. Bruce, upon recommendation of the Committee on Science and the Arts, which has just been read, I present to you this Longstreth Medal with much pleasure."

Mr. Bruce was much gratified by this recognition of his work.

To Messrs. Howard D. Colman, Rockford, Illinois, and Burt A. Peterson, Rockford, Illinois. Mr. Charles H. Masland, 2nd, sponsor.

The President called upon Mr. Masland.

Mr. Masland: "Mr. President, I wish to present Mr. Howard D. Colman and Mr. Burt A. Peterson of Rockford, Illinois, to receive a Longstreth Medal 'in consideration of the signal advance in the art made by the Barber-Colman Automatic Spooler and of the general excellence of its design.'

"Unfortunately Mr. Colman is unable to be present, Mr. Peterson therefore will receive the medals on behalf of himself and his co-worker."

The President presented the Medals as follows: "Mr. Peterson, I am glad to make this joint award to you and Mr. Colman. We are pleased to have you with us and hope you will convey our good wishes to Mr. Colman."

Mr. Peterson: "I thank you very much, sir."

To Mr. Peter Davey, New York City. Mr. William H. Kavanaugh, sponsor.

The President called upon Mr. Kavanaugh.

Mr. Kavanaugh: "Mr. President, I sponsor Mr. Peter Davey of New York City, who has been awarded a Longstreth Medal 'in consideration of the successful and useful

combination of well-known principles embodied in the Vibroscope and the Vibrometer and especially of their combination in a portable balancing device.'"

The President presented the medal as follows: "Mr. Davey, in accordance with the citation just read, I am most happy to present to you this Edward Longstreth Medal."

Mr. Davey said: "I appreciate deeply this honor."

To Mr. Karl B. McEachron, Pittsfield, Massachusetts. Mr. William G. Ellis, sponsor.

The President called upon Mr. Ellis.

Mr. Ellis: "Mr. President, Mr. Karl B. McEachron of the General Electric Company, Pittsfield, Massachusetts, is recommended for a Longstreth Medal 'in consideration of his careful conduct of a series of closely controlled investigations extending over a period of six years which resulted in the successful development of a process for manufacturing Thyrite.'"

The President presented the medal as follows: "We hope you will feel, Sir, that this award is some slight recompense for your long years of research. The Franklin Institute is very happy to make this presentation to you."

Mr. McEachron was much gratified by this award to him.

PRESENTATION OF WETHERILL MEDALS.

To Dr. Francis F. Lucas, New York City. Dr. Thomas D. Cope, sponsor.

The President called upon Dr. Cope.

Dr. Cope: "Mr. President, upon recommendation of the Committee on Science and the Arts of The Franklin Institute, Dr. Francis Ferdinand Lucas of the Bell Telephone Laboratories, has been awarded the John Price Wetherill Medal 'in consideration of his development of a technique of microscopy and photomicrography by virtue of which objectives of the highest numerical aperture yet developed and visible light and ultra violet light have been brought to their full theoretical resolving power, and by the use of which photomicrographs of metallurgical and biological specimens superior to any heretofore made are now being produced under his direction.'"

The President presented the medal as follows: "Dr. Lucas, I feel, that by virtue of your brilliant contributions

to knowledge, it is very fitting that our great Institute of science should bestow this award upon you—an important worker in a great research laboratory where efforts are constantly made to further the cause of science."

Dr. Lucas expressed warm appreciation of the honor bestowed upon him.

To Mr. Robert E. Naumburg, New York City. Mr. Lionel F. Levy, sponsor.

The President called upon Mr. Levy.

Mr. Levy: "Mr. President, the Board of Managers has sanctioned our Committee's recommendation that a Wetherill Medal be presented to Mr. Robert E. Naumburg 'in recognition of an invention which embodies a meritorious utilization of several well-known mechanical and physical principles to produce an apparatus original in its accomplishments and of unquestioned benefit to humanity.'

"I therefore have much pleasure in presenting to you, Mr. Naumburg."

The President presented the medal as follows: "Mr. Naumburg, The Franklin Institute is pleased to have this opportunity to recognize as evidenced by this Wetherill Medal, an invention which is so helpful to the blind. By your skill, you have lightened their darkness and we hasten to join with them in expressing our appreciation."

Mr. Naumburg very graciously expressed his gratitude.

To Messrs. W. H. Shortt, Exeter, England, and F. Hope-Jones, London, England. Mr. James Stokley, sponsor.

The President called upon Mr. Stokley.

Mr. Stokley: "Sir, it is my privilege to sponsor the award of a Wetherill Medal to Messrs. William Hamilton Shortt and F. Hope-Jones of England. This award is made 'in consideration of their respective contributions to the invention, development and production of a free pendulum type of clock of remarkable precision, which is now used in standard time control in Great Britain and the United States.'

"Unfortunately, Mr. Shortt is unable to be present. Mr. Hope-Jones has made the long journey expressly to participate in our exercises and to receive the medals in behalf of Mr. Shortt and himself."

The President presented the medals as follows: "Mr.

Hope-Jones we are especially glad to make this award to you who has travelled three thousand miles to receive it. I hope you will express to Mr. Shortt the high admiration which we have for the work which you have both done."

In accepting the award Mr. Hope-Jones said: "I claim the privilege of thanking you on behalf of my colleague, Mr. W. H. Shortt, who could not be here in person, and myself. We have worked together, and, as you never can tell when the flint and the steel, struck together, will really draw the spark, so it is with a joint invention. I am sure, however, that in this particular case, Mr. Shortt should receive the greater part of honor for our work."

To Dr. James E. Shrader, Philadelphia. Mr. C. W. Bates, sponsor.

The President called upon Mr. Bates.

Mr. Bates: "Upon the recommendation of the Committee on Science and the Arts, I present to you Dr. James E. Shrader of Drexel Institute to receive a Wetherill Medal 'in consideration of the design and construction of a portable and easily operated instrument for the investigation of vibrations, which affords simultaneous records of the vibrations, in three mutually rectangular directions, and in which the inventor displayed much ingenuity.'"

The President presented the medal as follows: "We are very glad Sir, to pay honor to you for your helpful contributions to engineering and it adds to our pleasure in that we honor in you a member of a sister institution."

Dr. Shrader expressed his thanks for this honor.

To Dr. Louis B. Tuckerman, Washington, D. C. Dr. Winthrop R. Wright, sponsor.

The President called upon Dr. Wright.

Dr. Wright: "Mr. President, it is recommended that a Wetherill Medal be presented to Dr. Louis B. Tuckerman of the Bureau of Standards in Washington 'in consideration of the fundamental improvements which he has introduced into the optical lever, making it an instrument of hitherto unrealized precision, and of his ingenious application of this lever to a strain gauge.'"

The President presented the medal as follows: "Dr. Tuckerman, we are delighted to honor you because of your

brilliant work and for your connection with the Bureau of Standards. The Franklin Institute admires that organization for the calibre of its scientific work and at the same time looks upon it with pride because the original suggestion for the establishment of a Bureau of Standards by the Government came from a member of The Franklin Institute who appeared before a Senate Committee in advocacy of the establishment of such a department."

Dr. Tuckerman expressed his thanks for this honor.

To Mr. Henry E. Warren, Ashland, Massachusetts. Mr. Charles E. Bonine, sponsor.

The President called upon Mr. Bonine.

Mr. Bonine: "Mr. Chairman, the Board of Managers has sanctioned the award of a Wetherill Medal to Mr. Henry Ellis Warren of Ashland, Massachusetts, 'in consideration of his invention of the Telechron motor—a small, limited-power, self-starting synchronous motor having strong starting torque and synchronous torque characteristics.'

"I therefore present to you Mr. Warren, to receive this award."

The President presented the medal as follows: "In accordance with the report just read, I hand you this Wetherill Medal. As the representative of engineers, I wish to express our appreciation of the great value of your ingenious invention."

Mr. Warren was greatly pleased to be the recipient of an award from The Franklin Institute.

Another selection of music: "Capriccio" by Haydn was then rendered.

PRESENTATION OF THE CLARK MEDAL.

To Mr. Frederick J. West, Manchester, England. Received by the British Consul General in Philadelphia, Mr. Frederick Watson. Mr. John B. Klumpp, sponsor.

The President called upon Mr. Klumpp.

Mr. Klumpp: "Mr. President, it is my privilege to present to you, in absentia, Mr. Frederick Joseph West of Manchester, England, who has been awarded the Walton Clark Medal 'in consideration of his outstanding service to the Gas Industry in the sphere of improved scientific development of gas works

practice and technique and practical gas research as applied particularly to the carbonization of coal in vertical retorts, and for his work in the training and education of engineers and his success in promoting amicable relationships between employer and employed, all of which have been of substantial value to the Manufactured Gas Industry.'

"Mr. West was unable to come to America to receive this award in person. He has written however to express his keen appreciation of this award. In his absence it will be received by Mr. Frederick Watson, the British Consul General in Philadelphia."

The President presented the medal as follows: "Mr. Consul General, we are gratified to find that year after year we have cause to present medals to you, who receive them with such grace. This year our Clark Medal, established in memory of a man whom you knew and we all loved, goes to Mr. West for outstanding accomplishment. Will you be good enough to convey it to him with our good wishes?"

The British Consul General responded: "Mr. President, it gives me much pleasure today to be here at your meeting. When I was asked to take this award I understood that it was made of a baser metal than gold but now that I know that it is a gold medal I hope you will put someone about to watch me carefully.

"If I may, I would like to have the privilege of reading this message which Mr. West addressed to Dr. McClenahan. It is as follows: 'Regret very much unable to attend to receive Walton Clark Gold Medal in Person. Please accept my highest appreciation of honour. Award considered also as honour conferred upon British Gas Industry Giving great satisfaction in this country.

Fred West.'"

PRESENTATION OF THE LEVY MEDAL.

To Dr. Harold L. Hazen, Cambridge, Massachusetts. Dr. George S. Crampton, sponsor.

The President called upon Dr. Crampton.

Dr. Crampton: "Mr. President, I beg to present Dr. Harold L. Hazen of the Massachusetts Institute of Technology to receive the Levy Medal for his papers on 'Theory of Servo-

Mechanisms' and 'Design and Test of a High Performance Servo-Mechanism.' This medal is presented upon the recommendation of the Committee on Science and the Arts for that paper which appears in the Journal of The Franklin Institute for the preceding year which is voted to have the highest merit in point of research and literary style."

The President presented the medal as follows: "Dr. Hazen, as the man who receives the Levy Medal, which I now have the honor to present, you do not come to this meeting a stranger. Those of us who read the JOURNAL have already made your acquaintance through your papers in that august publication."

Dr. Hazen responded: "It is a great honor to receive this medal. I wish to express my sincere appreciation to you as the President of this Society for this encouragment to go on to further endeavor."

AWARD OF FRANKLIN MEDALS.

To Albert Einstein, Ph.D., F.R.S., Institute for Advanced Study, Princeton, New Jersey. Dr. Frederic Palmer Jr., sponsor.

The President called upon Dr. Palmer.

Dr. Palmer: "I have the honor to present to you, upon the recommendation of the Committee on Science and the Arts, Doctor Albert Einstein, as the recipient of a Franklin Medal 'in recognition of his contributions of fundamental importance to theoretical physics especially his work on Relativity and the Photoelectric Effect.' When Doctor Einstein was but twenty-six years of age he published the Special, or Restricted, Theory of Relativity which indicates that uniform motion is always relative; absolute motion is impossible. This theory brought about new concepts of space and time, and provided a new physical law of great importance, namely, that mass and energy are equivalent.

"Ten years later Doctor Einstein published his General Theory of Relativity, of which the Restricted Theory was a special case. The general theory set forth a new conception of the nature of gravitation and predicted an interaction between gravitation and light which astronomers were quick to put to the test. As a final contribution to the theory of

Relativity, Doctor Einstein announced a unified field theory, that is, a single mathematical equation so general in form that it includes both the law of gravitation and the law of electro-magnetism.

"When in 1900 Planck proposed the quantum theory of radiation and absorption of energy, Einstein had only just completed his university training. Nevertheless he recognized the far-reaching and revolutionary implications of Planck's theory. In dealing with the transformation of Planck's light quanta when they strike upon matter, Doctor Einstein discovered his famous law of the Photoelectric Effect, which brought order out of a chaotic mass of experimental data and laid the foundation for the science of Photoelectricity.

"The development of still another field of science was due, in part, to the imaginative ideas of Doctor Einstein, who extended De Broglie's theory of matter waves in such a manner that Schrödinger was able to propose his well known theory of Wave Mechanics.

"Doctor Einstein has occupied professorships at Zurich and Prague, and a special position was created for him as Director of the Kaiser Wilhelm Physical Institute. He has been elected to membership in the Royal Society, the Amersterdam Academy, and the Copenhagen Academy. Honorary degrees have been conferred upon him by the universities of Geneva, Manchester, Rostock and Princeton. He received in 1921, a Nobel Prize; in 1925 the Copley Medal of the Royal Society; in 1926 the gold medal of the Royal Astronomical Society. At present he is a member of the staff of the Institute for Advanced Study in Princeton.

"Through more than a hundred scientific papers, characterized by keen analysis and brilliant imagination, Doctor Einstein has exerted a profound and lasting influence upon the scientific thought of the world. The romance of his achievement has been such that mathematical physics has become popular with the public.

"Mr. President, it is an honor for us to have Doctor Einstein with us today and to bestow upon him the Franklin Medal."

The President then presented the Medal, the Certificate

and the Certificate of Honorary Membership as follows: "By authority vested in me as President of The Franklin Institute, I have the honor to present to you the Franklin Medal, the highest award the Institute grants, and with it I hand you a Certificate of Honorary Membership in The Franklin Institute. That the name of the man whose mathematical imagination has changed the line of thought of every physicist and mathematician in the world, should be added to the list of distinguished names of Franklin Medalists, is a fact in which we all rejoice."

Dr. Einstein: "I feel happy to have this honor and I feel more happy to be here with you today. I thank you."

To Sir Ambrose Fleming, M.A., D.Sc., Hon. D. Eng., F.R.S., Emeritus Professor, University of London, London, England. Dr. Frederic Palmer, Jr., sponsor.

The President called upon Dr. Palmer.

Dr. Palmer: "Mr. President, your Committee on Science and the Arts recommends that a Franklin Medal be awarded to Sir John Ambrose Fleming 'in recognition of his many contributions to the improvement of the art of communication, and especially the invention of the thermionic valve which bears his name.'

"Sir Ambrose was born at Lancaster, England, in 1849. During his education as an engineer at University College, London, the Royal College of Chemistry and St. John's College, Cambridge, he was the recipient of an unusual number of collegiate honors. In 1885 he became the first occupant of a newly created chair of electrical engineering at University College, London, a position which he held until his retirement in 1926.

"His wide interests and his ability as an electrical engineer secured his appointment as scientific adviser successively to the Edison Telephone Company, the Edison Electric Light Company, the Edison and Swan Company, and the Marconi Wireless Telegraph Company. With the last named company he helped to design and to construct the first long distance wireless station at Poldhu.

"During the early years of this century Sir Ambrose was led to an extended study of a phenomenon previously observed by Edison, namely, that of thermionic emission, with

the result that in 1904 he made the first form of thermionic valve. This constitutes one of the basic factors which have made possible the tremendous advance in the science of Radio Communication with which we are all familiar.

"Sir Ambrose is an Honorary Fellow of St. John's College, Cambridge; an Honorary Fellow of University College, London; an Honorary Member of the Royal Philosophical Society of Glasgow; a member of the Royal Institution of Great Britain; and has been President of the Victoria Institute and Philosophical Society of Great Britain, and Vice-President of both the Institution of Electrical Engineers and the Physical Society of London, the latter of which he helped to organize.

"Twice he has been awarded the Institution Premium of the Institution of Electrical Engineers. He has also been the recipient of the Hughes Gold Medal of the Royal Society, the Albert Medal of the Royal Society of Arts, the Faraday Medal of the Institution of Electrical Engineers, the Duddell Medal of the Physical Society, and the gold medal of the Institute of Radio Engineers, U. S. In 1929 he was created Knight. By his contributions to the art of electrical communication carried out through an unusually long and productive life, Sir Ambrose has helped to bring closer together the peoples of the world."

In the absence of Sir Ambrose the British Ambassador had been invited to attend the exercises and to receive the medal. Unfortunately he was detained in Washington and was unable to keep this appointment. We request, therefore, that the certificate and award be presented to the Secretary to be forwarded by him to Sir Ambrose Fleming. The President presented the medal, the certificate and Certificate of Honorary Membership as follows:

"As President of The Franklin Institute I have the honor to present to you, sir, this Franklin Medal and Certificate of Honorary Membership which I would ask you to forward to Sir Ambrose Fleming, whose valve, like the magic carpet, has brought the farmer in remote places to the center of the world."

Dr. McClenahan, the Secretary, stated that he would obey the President's directions.

The President then called upon the Secretary of the Institute to read an original paper which had been prepared by Sir Ambrose Fleming especially for this meeting. Dr. McClenahan addressed the meeting as follows:

"About as half as many years ago as Sir Ambrose Fleming has lived, I was a student of electrical engineering. In our work we used to know Sir Ambrose's delightful books. At this time I feel that most of my knowledge of electrical engineering has been due to that which I got from the results of his brain children and so in arranging for the presentation of Sir Ambrose's paper to you this afternoon I asked if I might have the pleasure of reading it in his absence. I feel that in so doing I would be repaying in some small part the debt of gratitude that I feel toward him."

Dr. McClenahan then read the paper entitled "The Thermionic Valve in Scientific Research" which is printed in full in this issue of the JOURNAL (page 151).

After the reading of the paper the President announced that a special showing of the planetarium would be given for the entertainment of the medalists and their friends. He invited all present to attend this special demonstration.

There being no further business the President dismissed the meeting with an expression of appreciation to all those who had attended and had participated in the exercises.

A dinner in honor of the medalists was held in the evening at the Bellevue-Stratford Hotel, at which time Dr. Albert Einstein was the guest of honor.

At the dinner Mr. Hayward, the President, paid a tribute to Dr. Howard McClenahan who on this date celebrated his tenth anniversary as Secretary and Director of The Franklin Institute. The President announced that a bronze plaque had been presented to the Institute in recognition of the fine services rendered by Dr. McClenahan during his term of office.

NOTES FROM THE U. S. BUREAU OF STANDARDS.*

TWENTY-FIFTH NATIONAL CONFERENCE ON WEIGHTS AND MEASURES.

The twenty-fifth meeting of the National Conference on Weights and Measures was held at the Bureau on June 4 to 7, inclusive. Although initiated in 1905 as an annual conference, no meetings have been held since 1931, because of adverse business conditions.

The Conference, which is sponsored by the Federal Government through the National Bureau of Standards, is an organization composed primarily of State and local weights and measures officials, designed to protect consumer purchasing as well as to effect commercial economy and efficiency by development of codes of specifications and tolerances for weighing and measuring devices, and to promote uniformity in weights and measures supervision throughout the United States.

One hundred and three State officials from Maine to Florida and as far west as Arizona were in attendance, as well as over 50 manufacturers of equipment. In all, 22 States and the District of Columbia were represented. In view of the fact that supervision of weights and measures has not as yet been provided, or is inadequately maintained, in about one-quarter of the States, the attendance this year may be considered as exceptionally representative of existing national activities. On the other hand, the situation in States which have been backward in developing proper control over weights and measures is, with betterment and standardization of existing administration, one of the primary considerations of the National Conferences.

The opening address on June 5 was delivered by E. C. Crittenden, Assistant Director of the Bureau in charge of research and testing. In the absence of Secretary Roper,

* Communicated by the Director.

Assistant Secretary of Commerce John Dickinson delivered the principal address Thursday morning, June 6. Other Federal officials who appeared on the program were A. S. McAllister, Assistant Director of the Bureau in charge of commercial standardization; F. S. Holbrook and H. W. Bearce, co-chiefs of the Division of Weights and Measures, H. C. Dickinson, chief of the Heat and Power Division, and Ralph W. Smith, chief of the section on weights and measures laws and administration, of the Bureau; and W. S. Frisbie and L. C. Carey, of the U. S. Department of Agriculture.

Since the last national conference in 1931 the organization had lost, by death, its president, Dr. George K. Burgess, then director of the National Bureau of Standards, and, by retirement, the first and second vice-presidents, former weights and measures officials of Indiana and Pennsylvania. The new officers chosen for the coming year are: President, Dr. Lyman J. Briggs, Director, National Bureau of Standards; First Vice-President, John P. McBride, Director of Standards, Commonwealth of Massachusetts, Boston, Mass.; Second Vice-President, C. D. Baucom, Superintendent of Weights and Measures, State of North Carolina, Raleigh, N. C.; Third Vice-President, Martin L. Lang, Commissioner of Weights and Measures, State of Indiana, Indianapolis, Indiana; Fourth Vice-President, J. C. Tinkey, Deputy Sealer of Weights and Measures, State of Ohio, Columbus, Ohio; Secretary, F. S. Holbrook, co-chief, Division of Weights and Measures, National Bureau of Standards, Washington, D. C.; Treasurer, George F. Austin, Jr., Supervising Inspector, Bureau of Weights and Measures, Detroit, Michigan.

George M. Roberts, Superintendent of Weights, Measures and Markets of the District of Columbia, at the head of the District delegation, related the local experience in "undercover" buying as an aid to proper weights and measures enforcement. The annual national consumption of sixteen billion gallons of gasoline alone is indicative of the possible purchaser loss through unregulated and unchecked measuring and dispensing devices provided for automobile fuels.

Two bills pending before Congress received attention. The Byrd bill to consolidate Federal standard container legislation was discussed by L. C. Carey, of the Bureau of

Agricultural Economics, Department of Agriculture, and the weights and measures provisions of the Copeland bill to revise the Federal food and drugs act were presented by W. S. Frisbie, chief of the Division of State Coöperation, Food and Drug Administration, U. S. Department of Agriculture.

Exhibits of weighing and measuring devices, confined to apparatus developed or marketed since the last conference in 1931, included several of particular interest to the consumer, such as the new grocery scales which reveal to the purchaser automatic price computations as well as those of weight. New types of market scales, with springs constructed of special materials and designed to function accurately regardless of temperature and climatic changes; scales with automatic printing attachments; devices for the long-distance electric recording of weighing results; automatic gasoline measuring and price computing apparatus; and scales specially designed for weighing airplanes were on view.

"Bootlegging"—the traffic in coal, gasoline, etc., from unknown sources, with difficulties arising in respect to weights, quality, and taxation—still presents a problem to all weights and measures officials and again appeared on the program with addresses and papers from several officials. S. T. Griffith, Chief of the Bureau of Weights and Measures of Baltimore, spoke on "The Control of 'Bootleg' Coal." S. H. Wilson, Oil Chemist of the State of Georgia, dealt with "Non-tax Paid Gasoline and Oil."

Philadelphia has instituted a somewhat unique board of arbitration, designed to consolidate the interests of all city weights and measures activities and representatives of various merchants' trade associations who meet frequently to consider reports of violations, applications for licenses, and matters of general administrative policy. The exceptional results, which may lead to adoption of the plan by other cities, were presented by Edwin C. Emhardt, Supervisor of the Bureau of Weights and Measures, Philadelphia.

Others appearing on the program included C. D. Baucom, Superintendent of Weights and Measures, of North Carolina, "Weights and Measures Regulations"; B. W. Ragland, Chief of the Bureau of Weights and Measures, Richmond, Virginia, "Temperature of Gasoline in Underground Storage"; D. V.

Stroop, Secretary of the Division of Marketing, American Petroleum Institute, "Petroleum Products"; Martin L. Lang, Commissioner of Weights and Measures, Indiana, "Sealed Cans for Lubricating Oil"; M. J. J. Harrison, Chairman of the Committee on Yards and Terminals of the American Railway Engineering Association, "Motor Truck Scales"; Willard E. Reed, Superintendent of Weights and Measures, Newark, N. J., "Testing of Beer Barrels"; J. C. Tinkey, Deputy State Sealer, Ohio, "Positioning of Scales for Customer Observation"; and E. B. Holton, Assistant Superintendent of Weights and Measures, New Jersey, "Supervision Over the Buying of Old Gold."

Sessions of the Conference during the first three days were held in the East Building of the Bureau and that on the concluding day at the Washington Hotel. The proceedings of the conference will appear later, in printed form, as a Miscellaneous Publication of the National Bureau of Standards.

THIRTEENTH ANNUAL CONFERENCE OF STATE UTILITY COMMISSION ENGINEERS.

The thirteenth annual conference of State Utility Commission Engineers was held at the Bureau on June 6–8. Twenty-six engineers, representing the Commissions of the States of Connecticut, Florida, Maine, Maryland, Missouri, New Hampshire, New York, Ohio, Pennsylvania, South Carolina, Tennessee, Vermont, Washington, West Virginia, and Wisconsin, and the District of Columbia, attended the sessions. Representatives from the Federal Power Commission, Interstate Commerce Commission, Rural Electrification Administration, and the Bureau of the Census were present at one or more sessions.

The following papers were read: "Taxes Paid by Utilities," Harry Barker, Vermont; "Effect of Recent Court Decisions on Utility Regulation," J. W. Carey, Washington; "Cost of Electrical Distribution," G. H. Morse and C. R. Bennett, Federal Power Commission; "Effect of the High Cost of Wiring and Appliances on the Use of Electrical Energy," J.

C. Damon, Wisconsin; "Some Thoughts and Discussion Regarding Water Utility Service and Regulation," John E. Goodwin, Maine; "The Telephone Industry," A. B. Greene, Florida; "Economic Investment in Transmission Equipment," R. E. Purucker, G. P. Steinmetz and W. A. Kuehlthau, Wisconsin; "Factual Data—Propane and Butane Plants in Maryland," Charles E. Thornton, Maryland; "Bus Transportation, Service, Safety, Rates, Effect of Motor Bus Code," Joseph T. Wadhams, Connecticut; "Discussion of Bus Transportation," H. C. Eddy, New Jersey; "Determination of the Physical Condition of a Pipe Line," K. H. Logan and I. A. Denison, National Bureau of Standards.

A small number of each of these papers is available for distribution to State utility commission engineers upon application to the secretary of the Conference.

The Conference was in charge of an executive committee of engineers as follows: Harry Barker, chairman, Vermont; P. L. Holland, vice-chairman, Maryland; J. H. Wiley, North Dakota; L. G. Krause, Pennsylvania; E. H. Morris, West Virginia.

The executive committee elected to make arrangements for the 1936 Conference is as follows: P. L. Holland, chairman, Maryland; A. B. Greene, vice-chairman, Florida, E. H. Morris, West Virginia; M. R. Williams, Tennessee; J. W. Carey, Washington, J. Franklin Meyer, National Bureau of Standards, Washington, D. C., is the secretary of the Conference.

THERMAL SPALLING OF FIRE-CLAY BRICK.

A discussion of the probable relation between linear thermal expansion, modulus of rupture, modulus of elasticity, and the resistance of fire-clay brick to thermal spalling is presented by R. A. Heindl in a current issue of the American Refractories Institute Bulletin.

Because of the readiness with which the linear thermal expansion of the usual type of fire-clay brick decreases, or in the case of the siliceous type of brick increases, when heated

to a temperature higher than that reached during the manufacturing process, and also because of the temperature gradient in bricks which are being heated or cooled (as in furnace walls), large stresses may be set up in the bricks. Unless the bricks have the necessary extensibility, or ability to "stretch" a suitable amount to permit adjustment of the various sections of the brick to these stresses, rupture will take place. The extensibility of refractory bricks or shapes is decreased as a rule (*a*) with increase of temperature of firing during manufacturing, (*b*) by using comparatively fine grog sizes in their composition, (*c*) by decreasing the amount of grog. Refractory shapes apparently show less resistance to thermal shock if they contain vitreous rather than porous grog. Furthermore, of two brands of bricks which have approximately the same properties at room temperature, the brand showing the greatest decrease in extensibility between room temperature and 600° C. (1,112° F.) will have the lower resistance to thermal shock.

Values for Young's modulus of rupture are compared for individual units of the same brand of bricks as well as of specimens cut from different parts of the same unit to show the uniformity of the product. A comparison of the elasticity values obtained on two units each of three brands of bricks showed the difference between the two units to range from about 0 to 72 per cent. However, when comparing the values obtained on six specimens from one brick, the modulus of elasticity may vary more than 180 per cent.

DETERMINATION OF BORIC OXIDE IN GLASS.

In a note in Technical News Bulletin No. 206 (June 1934) a modified method for the determination of boric oxide in glass was outlined. Since then it has been found that the final para-nitro-phenol end point is not always sharp enough to give satisfactory results. This condition apparently results either from small amounts of impurity in the ether or from allowing the alkaline ether-alcohol solution to stand too long before complete removal of the ether and alcohol.

Impurities in the ether were successfully removed by passing it in a very fine stream through alkaline permanganate of potash (adapted from Palkin and Watkins, Ind. & Eng. Chem., **21**, 863 (Sept. 1929)). The long contact is avoided by promptly removing the ether and alcohol by evaporation and subsequent boiling.

Instead of using 51.2 per cent. of the proportional amount of boric oxide extracted by the 50 ml. aliquot, it has been found more satisfactory to compute the boric oxide in the sample from the "distribution constant," which has been found to be 0.406. If A represents the amount of boric oxide, determined by titration, in 1 ml. of the 50 cc. aliquot of the ether-alcohol layer, 2.463 A represents the amount of boric oxide in 1 ml. of the water layer. The total boric oxide in the sample becomes the sum of the products of A times the total volume of the ether alcohol layer, and 2.463 A times the total volume of the water layer.

Following the above procedure, boric oxide has been determined in glasses and synthetic mixtures containing from 0.7 to 12.6 per cent. with an average error of 0.08.

The method has been found satisfactory for all glasses studied except those containing zinc, barium, and fluorine. These three elements interfere and cause low results.

RELATION OF GRAIN SIZE TO CONDITION OF ALUMINUM-ALLOY PROPELLER BLADES.

The periodic inspection of aluminum-alloy airplane propeller blades, as practiced by some users, consists in anodic etching of the entire blade surface. In this way surface discontinuities are made more prominent and so are more easily detected. The grain structure at the surface of the metal is also revealed. The fact that in many blades the anodically etched surface shows a marked variation in grain-size in different parts of the blade has often aroused suspicion concerning blades otherwise satisfactory in their appearance. Recently the Bureau made a survey, by metallographic

examinations and tensile strength determinations, of an alloy blade showing marked local differences in grain-size.

The smallest grains were found in the round shank and the tip of the blade, whereas extremely large grains were found in the middle part of the blade. In general, the grain-size seen on the surface persisted throughout the thickness of the blade. The highest tensile and yield strengths were obtained for the specimens from the shank. Specimens from the flattened portion of the blade did not differ significantly in strength, but the ductility, as measured by elongation and reduction of area of the fractured tensile test specimens, increased progressively from the shank to the tip, probably in accordance with the increase in amount of deformation in forging the blade to shape. In general, the results did not support any general condemnation of propeller blades on the basis alone of unusual grain-size characteristics.

PREPARATION OF LARGE SINGLE CRYSTALS OF COPPER.

The crystals which constitute a metal are ordinarily too small to permit their separation and the determination of the properties of the individual crystals. Several methods, however, have been developed for the laboratory preparation of metallic crystals so large that test specimens can be prepared, each consisting of only one crystal. In the section of chemical metallurgy at the Bureau a modification of the Bridgman method has been employed, whereby single crystals of copper several inches in length and up to $2\frac{1}{2}$ inches in diameter were prepared. Orientation of the structure in these single crystal specimens was determined by means of selective etchants which reveal the location of certain of the crystal faces.

PERMANENCE OF WRITTEN SIGNATURES.

Recently a letter was received at the Bureau concerning the fading of signatures on important documents. In its

printed publications and in replies to individual inquiries the Bureau has many times referred to the bad practice of using a blotter to dry signatures on documents which should remain legible for many years.

On important state papers, commissions, and legal documents a blotter should never be used. Its employment in a busy office can be excused, particularly as most correspondence is only of temporary value, but it should always be remembered that to remove the greater part of the ink instead of letting it soak into the paper and dry there, shortens the life of the writing. This is entirely apart from the quality of the paper, which, in ordinary correspondence, may not be good enough to justify much worry as to the permanence of the ink signature. In the case of important documents it is of course understood that a high grade permanent paper will be used.

ACCELERATED SETTLING TEST FOR PAINT.

An iron oxide paint, to be used as an automobile primer, was found to pass the current Federal Specification in all respects, when tested at the Bureau last February. Three months later this primer was found to be badly settled in the container. The type of settling was a hard, dry cake in the bottom of the can. This suggested the development of an accelerated settling test to predetermine the settling tendencies of a paint, particularly one freshly manufactured. The following simple test was found satisfactory:

> Pour 250 ml. of the mixed paint in a 12-ounce screw cap, glass bottle (2¼ inches inside diameter). Let stand 18 hours at 90–100° F. Centrifuge for ½ hour at 750 r.p.m. at a radius of 6½ inches. Let stand 5 hours at 90–100° F. Centrifuge for another ½ hour at 750 r.p.m. Repeat this cycle for another 24 hours (48-hour test). The layer of settled pigment shall be *soft*, not hard and dry. Using a stirring rod (not over 6 mm. diameter), the paint (without pouring off the liquid) shall mix within one minute to a uniform condition and give a smooth film.

The sample in question would not pass this specification, while others known to have good settling properties passed the test. For this type of paint it is estimated that the accelerated test is equivalent to about 6 months of normal shelf storage.

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Mr. William Stanton Monroe, Sargent and Lundy Inc., 140 South Dearborn Street, Section 3, Old Post Office Annex, Chicago, Illinois.

Mr. Richard Maxwell Pearl, 12755 Evanston Avenue, Detroit, Michigan.

Mr. Francis R. Wadleigh, 806 Prince Street, Alexandria, Virginia.

LIBRARY NOTES.

RECENT ADDITIONS.

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BOOK REVIEWS.

WIRELESS RECEIVERS, THE PRINCIPLES OF THEIR DESIGN, by C. W. Oatley, M.A., M.Sc., with a preface by O. W. Richardson, F.R.S. 103 pages, diagrams, 11 × 17.4 cms. London, Methuen & Co., Ltd. New York, E. P. Dutton & Co., Inc. Price eighty-five cents.

This little book, about the size to fit conveniently into one's pocket, is one of the series of Methuen's Monographs on Physical Subjects, the purpose of which is to supply readers of average scientific attainment with a compact statement of the modern position in each subject. After giving attention to a brief introduction on the function of a wireless receiver and different types of distortion of the signal, the author treats on the various stages of the receiving apparatus, i.e., the high frequency detector, low frequency and power stages. A very necessary and noteworthy part of the work is that devoted to the triode and its equivalent circuit, and the picture, ably presented, of the aerial-earth system.

The book is not one for the uninitiated in technology but it is a valuable presentation for those qualified to absorb the information and who are not fully conversant with the subject.

R. H. OPPERMANN.

THE PRINCIPLES OF PHYSICAL METALLURGY, by Gilbert E. Doan, Ch.E., Ph.D. 332 pages, illustrations, tables, 15 × 23 cms. New York and London, McGraw-Hill Book Company, Inc., 1935. Price $3.00.

In this as in other physical fields, experiment plays a most important part in development. For this reason basic concepts must constantly be modified. This book gives an account of up to date knowledge.

It is divided into three parts; the physics of metals devoted to the states of aggregation, properties of metals, and the deformation and annealing of metals; metallography including the constitution and crystal structure of binary alloys, structures of ternary alloys, and the properties of alloys; metal technology on the shaping of metals, their treatment, and the testing of metals. Separate consideration of the commercial aspects of the principal metals and alloys is given briefly.

In conformity with the title of the book the approach to the subject is that of the classical physics and chemistry. The principles of metallic behavior are considered most important, not the individual alloys or processes, although because it is impossible to ignore the industrial importance of these, they are taken up to the necessary extent.

The book is profusely illustrated and contains much data, tabular and otherwise, to make it most useful and illuminating. It is undoubtedly a classic text and can be recommended to all whose interests lie in this direction.

R. H. OPPERMANN.

THE ART OF INVENTING AND WHAT TO INVENT, by Raymond F. Yates. 284 pages, plates, 13.5 × 21 cms. New York and London, D. Appleton-Century Company, Inc., 1935. Price $3.00.

Has a thought ever entered your mind while examining a modern automobile or domestic appliance that valuable patents may be obtained on very simple ideas? Most everyone has marveled at the simplicity of much of what is in every-

day use. If this thought has fathered the wish that you may some day invent something useful, this book is what you need. It is designed to help and encourage people who would invent but who, either because of pathetic respect for those who have succeeded, or because of firm belief in the need for that mysterious quality of genius, have made no effort to tap the well spring of their own creative faculty. It will help to dispel the belief that formal technical training is absolutely necessary. The successful achievements of men without this is proof on this point.

The book tells what an inventor should know about mechanics, chemistry, electricity, sketching and drawing and manufacturing methods. While it is not possible to actually reduce the method of inventing to an exact formula that will take into consideration the idiosyncracies of all those who would invent, methods are set down with practical limits. A considerable part of the book is devoted to patents—finding the right patent attorney, the preparation of patent claims, how inventions are sold, how to take out a patent, etc., as well as a reproduction in full of the "Rules of Practice of the United States Patent Office." A list of 77 needed inventions is given to help the inventor recognize the kind of things the public needs and to supply him with actual problems upon which he can exercise his ingenuity.

R. H. OPPERMANN.

ELECTRON EMISSION AND ADSORPTION PHENOMENA, by J. H. deBoer, translated from the manuscript by Mrs. H. E. Teves-Acly. 398 pages, illustrations, tables, 15 × 22 cms. New York, The Macmillan Company. Cambridge, England, University Press, 1935. Price $5.50.

This remarkable book is one of the Cambridge series of Physical Chemistry and was written at the suggestion of Professor E. K. Rideal during his visit to the Physical Laboratory of the N. V. Philips' Gloeilampenfabrieken in Eindhoven in March 1933. In an unusual style the author makes comparison of the photoelectric phenomena and the thermionic phenomena in the adsorption on metals in an endeavor to throw light upon the subject by the study of the phenomena of electron emission.

The book may be divided into two parts, the first containing two chapters of an introductory nature on electron emission from metals and on the nature of adsorption forces. These give a good foundation for the treatment which follows. Then there are four chapters on the influence on the emission of conduction electrons by the adsorption on metal surfaces. Here in the part devoted to adsorption of cæsium on tungsten surfaces reference is made to the work of Langmuir and Becker, the former making no or only a vague distinction between adsorbed atoms and adsorbed ions in the conception of the electrical double layer, and the latter who makes this distinction. The conception developed in the book coincides to a great extent with that of Becker, although there are several essential points of difference. Later in this part of the book, the study of photoelectric emission is taken up from the standpoint of the change in the photoemission of the supporting metal caused by the adsorption of electropositive atoms.

In the second part of the book the individual properties of adsorbed atoms are more emphasized. The absorption of light by matter in the gaseous state and in the adsorbed state are treated in detail and there is discussed the adsorption of alkali metal atoms within dielectrics, whereby the adsorbed atoms are not

found on the boundry surface between the dielectric and a vacuum, but in contrast are surrounded on all sides by the dielectric. After this it is shown that in many cases internally adsorbed atoms can give up their electrons under thermal influences. This thermal ionization which leads to an electrical conduction is essentially similar to the thermal ionization of atoms adsorbed on external surfaces.

The method of presentation of the subject matter makes use of potential curves to represent visually the relations between adsorbed atoms and ions and their adsorption energies.

Necessarily in order to make a presentation of this kind, the author has made reference to and very clearly indicated literature on the work of others throughout the book. There is also a subject and name index. The book is an admirable treatment and should stimulate further research.

R. H. OPPERMANN.

AN INTRODUCTION TO PHYSICAL SCIENCE, by Carl W. Miller, Ph.D., second edition. 409 pages, illustrations, 14.5 × 22 cms. New York, John Wiley & Sons, Inc., London, Chapman & Hall, Ltd., 1935. Price $3.00.

Anyone who has need for a brief, concise, and well written text on this subject either for study or reference purposes would certainly benefit by the use of this book. Its scope is from the beginning of scientific thought briefly to about the time of Galileo and through to the surprising results of modern research. To cover this field in a single volume in as comprehensive a manner as is here presented is an achievement worthy of special notice.

Mechanics, heat, light and sound, electricity and magnetism, radio to the quantum theory and cosmic physics are all given treatment. The author has followed as far as possible the historical development of the subject which produces a text easier to follow for many. This together with the absence of the derivation and use of many complex mathematical formulæ make it most appealing. The book however does not eliminate mathematics to the point of sacrificing a thorough treatment, but only avoids that which is unnecessary.

The author states in regard to the emphasis placed on experimental methods in this book that the goal of physical science is a fuller knowledge of the world in which we live, and the scientific method of approach to this goal is that of experiment, the formulation of hypotheses, and the checking of these hypotheses by still further experiment. Experiment is destined in the future as it has done in the past, to restrain us from too free speculation and to suggest new avenues of advance.

There are thirty-nine chapters devoted to as many subjects. Exercise problems appear at the end of each chapter and there is a very useful index in the back of the book.

Too much cannot be said with relation to completeness of treatment, in fact it is difficult to visualize this without a perusal of the book itself. The book is well suited to the needs of students who contemplate future work in other sciences, to the technical man for brushing up and refreshing his knowledge on any of the subjects coming under this heading, to the student who wishes to do home studying, and finally to all those who wish a book for references purposes.

R. H. OPPERMANN.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

Report No. 523, The Influence of Wing Setting on the Wing Load and Rotor Speed of a PCA-2 Autogiro as Determined in Flight, by John B. Wheatley. 4 pages, figures, 23.5 × 29 cms. Washington, Superintendent of Documents, 1935. Price five cents.

Flight tests were made on a PCA-2 autogiro with wing settings of 2.2°, 0.9°, and — 0.5°. The wing load and rotor speed were measured in steady glides. The results obtained show that a wide variation in rotor speed as a function of air speed can be obtained by a suitable adjustment of the wing setting; that by decreasing the wing setting the upper safe flying speed, determined by the decrease in rotor speed, is greatly increased; and that the interference of the wing on the rotor thrust and lift coefficients is negligible. The prediction of autogiro wing loads is assisted by the data given in this paper.

R.

IMPREGNATED PAPER INSULATION, THE INHERENT ELECTRICAL PROPERTIES, by J. B. Whitehead, Ph.D., Professor of Electrical Engineering, The Johns Hopkins University. 221 pages, tables, diagrams, 15.5 × 23.5 cms. New York, John Wiley & Sons, Inc. London: Chapman & Hall, Ltd., 1935. Price $4.00.

A book devoted to a much valued material for insulation for high-voltage power cables. As a matter of fact, impregnated paper is the material that limits in a large measure the voltage used in cables and in capacitators. Because of this there has been extensive study in manufacturers' and utilities laboratories with the object of improvement. The result has been noteworthy. The values of voltage-rating of power cables have increased ten fold in the past twenty-five years. But research is still in demand with relation to basic electrical behavior of the constituent materials with the view to discover underlying causes of major characteristics and so reveal the paths to better performance. This book gives an account of selected researches, united into one picture, carried out in the School of Engineering of Johns Hopkins University. The researches selected are those which seem to have the greatest bearing on present problems.

There are seven chapters in the book beginning with the physical properties and electrical characteristics of impregnated paper as insulation. Then there is a chapter on the electrical characteristics of dry paper covering the influence of moisture and temperature, followed by a chapter on the general electrical properties of insulating oils. Researches are described on the variations in power factor of impregnated paper as related to the amount of residual or entrained air, the results of which indicate that on impregnation a considerable amount of air which might still be in the paper can be absorbed by the oil. In convenient sequence to this treatment there is followed one on the capillary properties of papers and oils. Finally the properties of the assembled product are given attention with parts devoted to dielectric strength, loss and life.

The construction of the book deserves special mention. At the end of each chapter conclusions are drawn on the matter treated. Also there is an entire chapter on general conclusions as related to practice. They are brief and clear cut statements which should be of particular value to those readers generally familiar with the subject. Numerous articles and papers referred to throughout the book

are noted so that the book includes a representative bibliography. An appendix covers the pre-determination of the A-C characteristics of dielectrics—validity and sufficiency of experimental method—and includes parts on Von Schweidler's Analysis, the method of three exponentials, accuracy of the method, etc.

The book is the fourth in the series of monographs issued under the auspices of the Committee on Electrical Insulation, Division of Engineering and Industrial Research of the National Research Council. The author needs no introduction. His work is well known and his book is not only well written but probably gives a very much clearer and more intimate quantitative knowledge of the makeup of all electrical characteristics of impregnated paper than has been heretofore possible.

R. H. OPPERMANN.

THE FUNDAMENTALS OF RADIO, second edition, by R. R. Ramsey, Ph.D., Professor of Physics, Indiana University. 426 pages, tables, illustrations, 16 × 23.5 cms. Bloomington, Ramsey Publishing Company. Price $3.50.

A treatise on radio communication, comprehensive in scope but rather sketchy in the treatment of important detail. The author undertakes an ambitious program to cover so comprehensively such an involved subject in a little over four hundred and fifty pages.

The book will provide constructive material for the lay reader although some of the subject matter is rather historic in nature to merit the space afforded in a book of this type.

Three chapters are devoted to direct current and magnetism. The treatment savors of a textbook on physics. The lay reader is provided with much of an understandable, useful nature.

Four chapters deal with alternating current phenomena including rather careful treatment of resonance, self and mutual inductance, capacity.

Considerations involving the vacuum tube are deservedly given seven chapters, a most valuable section of the book. Practically every phase of electron tube action is well covered from the original two electrode value to the variable amplification pentode.

An unusually complete treatment of the mechanism of radiation includes considerations of the characteristics of the various antennae in use.

Additional subjects treated include radio and audio amplification as applied to both transmission and reception; measurements at radio and audio frequencies.

A chapter is devoted to loud speakers and the final chapter covers some recent applications of the vacuum tube in fields other than radio.

The book closes with a rather complete set of questions pertinent to the various chapters of such a nature as to encourage the student toward careful reading.

No bibliography is included, although there are many references throughout the text. Some tabulated data is to be found; this book, however, should be supplemented by a reliable hand book to be of maximum value for the practical worker.

WILLIAM G. ELLIS.

PUBLICATIONS RECEIVED.

The Fundamentals of Radio, 2d edition, by R. R. Ramsay, 426 pages, illustrations, 15 × 23 cms. Bloomington, Ind., Ramsay Publishing Company, 1935. Price $3.50.

The Principles of Physical Metallurgy, by Gilbert E. Doan, 332 pages, tables, illustrations, 15 × 23.5 cms. New York and London, McGraw-Hill Book Company, Inc., 1935. Price $3.00.

Electron Emission and Adsorption Phenomena, by J. H. de Boer, 398 pages, illustrations, tables, 14.5 × 22 cms. New York, The Macmillan Company, 1935. Price $5.50.

An Introduction to Physical Science, by Carl W. Miller, 409 pages, illustrations, 14 × 22.5 cms. New York, John Wiley & Sons, Inc., London, Chapman & Hall, Ltd., 1935. Price $3.00.

The Art of Inventing and What to Invent, by Raymond F. Yates, 283 pages, plates, 14 × 20.5 cms. New York and London, D. Appleton-Century Company, Inc., 1935. Price $3.00.

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CURRENT TOPICS.

Caliche.—D. G. RUNNER in an article in *Roads and Streets* for June 1935 presents information on the origin, properties and use of caliche. The material is a calcareous formation of varying thickness widely found in the semi-arid regions of the southwestern United States. It is being used in road construction in the southwest due partly to the lack of other road materials of suitable quality, and to excessive cost of shipped-in aggregate.

In western South America, the name caliche is applied to the deposits of crude soda-niter. In southwest United States it is essentially a lime carbonate, containing in addition, magnesium, alumina and calcium silicates, and is in decided contrast with the true caliche of Chile. The material possesses the property of hardening when wet, which feature is commonly utilized in constructing pavements. However, the scarcity of water in the arid sections made it necessary to obtain the desired compaction by other methods. It was found that crushing the caliche to smaller sizes aided somewhat in the dry compaction, and the finer the material was crushed the greater the ease of compacting when in a dry state. Usually the specifications for a caliche base require the material to be put down in two courses, the first course to be throughly wet and compacted before the second course is begun. The loose material laid at least 9 in. in depth, compacted to a thickness of 4½ in. The caliche, after wetting and rolling is allowed to "set up" before the second course is placed. Before putting on the top course, the base section is bladed even and brought to grade. The top course procedure is essentially the same as that employed in constructing the bottom course.

R. H. O.

Automatic Steam Turbine.—R. W. P. LEONHARDT (*Power*, Vol. 79, No. 6). In the new power house of Mitteldeutsches Kraftwerk, Magdeburg, Germany, house service energy is supplied from the 10,000 volt main station bus bars through 3 transformers which step down to 380 volts. For emergency service a 3,000 r.p.m., 400 lb. pressure, 770 degree turbine connected to a 700 Kva generator is connected in parallel with the transformers. It is arranged for automatic starting so that it is possible to have the unit supplying energy to important auxiliaries within 30 seconds. When the voltage fails across the 10,000 volt bus bars an under voltage relay

trips. A retarding device then interrupts the process of switching for a duration of 5 seconds so that the turbine does not start up unnecessarily should full voltage reappear across the bus bars. If voltage fails to reappear, a master relay switches into the circuit, causing the automatic starting process to continue. A series of relays operating in their proper order starts the turbine and when the generator voltage has reached 420 the three house transformers are disconnected and the main breaker of the emergency generatro is closed.

R. H. O.

The Moscow Subway.—(*Transit Journal*, Vol. 79, No. 6.) On April 22, the first section of 7.1 miles of the Moscow, Russia subway was completed. It connects two of the most populous suburbs through the heart of the business district. When the entire system is completed it will be about fifty miles long and it is laid out radially, twelve lines running outward from the central part of the city with a belt line joining the ends of the radiating subway lines. The diameter of the tunnels is 18 ft., permitting use of wide and comfortable cars. No two stations are exactly alike, which enhances architectural interest and aids passengers in identifying them. They are finished in marble, polished granite, majolica and nonferrous metals.

In tunneling, the natural difficulties were so great that in 1932, after 6,000 workers had unsuccessfully attempted a number of tunnels, several experts advised the abandonment of the project as impossible. Practically all known construction methods were tried out including the British shield system, the French caisson system, the Belgian double passage, artificial freezing and the American "flying arch." For tunneling through solid ground the latter was demonstrated to be cheaper and quicker than the Belgian method. Late in 1932, a method was discovered of treating the subsoil with chemicals which held the tunnel wall together until the concrete linings could be completed.

The cars are 61½ ft. long and built entirely of metal. Automatic devices stop them in the event the track ahead is occupied. It is estimated that the subway will carry about 128 million passengers this year.

R. H. O.

Standardized Rupture Disks.—(*Chem. & Met.*, **42**, 260.) The development of the frangible disk as a protective device for unfired pressure vessels has been given considerable impetus by the work of M. E. BONYUN. Briefly the tests consisted of fastening metal

disks over the discharge opening of a pressure vessel and building up the pressure to the point of the disk's rupture. The point of rupture of metals at different thicknesses was ascertained by numerous trials at a fixed diameter and, again, by varying the diameter and maintaining the thickness constant. From a mass of accumulated data, 100 per cent. fine silver, 99 per cent. pure nickel, electrolytic copper and aluminum were singled out as being best suited to the requirements desired. Commercially tinned sheet iron, brass, bronze, german silver, and Monel metal were unsatisfactory because these alloy metals did not show constant characteristics when rolled to the extreme thinness required.

By plotting the bursting pressure against the diameter of the disk a smooth curve could be obtained for any particular thickness of metal. It was found that the rupture points of diaphragms of pure metals, uniform in thickness, homogeneous in structure, and at atmosphere temperature, follow the function $P = C/D$ where P is the rupture stress, C is a constant varying with the kind and thickness of the metal and D is the disk diameter. This expression is similar to the equation of a hyperbola which is referred to its asymptotes as axes of coördinates.

Both 24-carat gold and No. 1 platinum proved to be suitable materials for rupture disks but the gold was eliminated in favor of platinum for several reasons. The latter is better constituted to resist chemical attack than is gold, particularly where the pressure vessels contain refrigerants such as sulfur dioxide and dichlorodifluoromethane. The hydrofluoric acid encountered with the latter presents the most serious corrosion problem to disk material. Platinum was found to be absolutely impervious to attack both by this and by sulfur dioxide. In addition, the melting point of platinum is 3190° F. as against 1,950° F. for gold. Also, gold has risen in price while that of platinum has fallen even more. The scrap value of the latter also is considerable.

As it appears that platinum will become so important as a rupture disk material, it is hoped that by careful homogeneous welding between thin sheets of it and nickel, the entire range of pressures can be covered with these two metals used separately and in combination. Although platinum has a high melting point, its tensile strength is only about 22,000 lbs. while that of nickel is between 50,000 and 70,000 lbs. after annealing.

C.

Industrial Scale Handling of Metallic Sodium.—(*Chem. & Met.*, 42, 264.) In a paper read at the twenty-seventh semi-annual meeting of the American Institute of Chemical Engineers P. J. CARLISLE

described the handling of sodium on an industrial scale. This highly reactive metal is now available in cast bricks weighing 1, 2.5, 12 and 24 lbs. For most industrial purposes the 12- and 24-lb. bricks may be fed directly into the reaction systems. If other shapes or sizes are desired, the sodium may be melted in a small round-bottom cast iron pot with drain and loose-fitting steel cover, with arrangement for maintaining an inert atmosphere in the pot. Heating may be by direct fire, or preferably by hot oil circulated in a jacket, or by electric resistance heaters.

A comparatively recent development is the shipment of solid sodium in tank cars, of about 80,000 lb. capacity, which may be filled in 16 hours and melted and unloaded in 13 hours. The car has steel coils welded on the outside surface through which cold oil is circulated during the filling and hot oil while unloading. In filling the air is displaced with nitrogen prior to admitting the sodium.

Large quantities of sodium may be conveyed from one nearby point to another by melting and conducting through a pipe line. In one installation, sodium has been transported for over two years in a 2½-in. welded standard iron pipe about 1,200 ft. long. Heating of this pipe is done by means of an electrical resistance, consisting of a welded 1/2-in. steel pipe mounted parallel to the pipe line and insulated from it. Sodium is caused to flow through the pipe line by applying a partial vacuum to the outlet end. On occasions this flow has been as great as 20,000 lbs. per hour.

C.

Alcohol and Gasoline Do Mix.—(*Chem. & Met.*, 42, 285.) At Dearborn, Mich., on May 7–8, nearly 150 men prominent in agriculture, industry and science opened a conference with the signing of a document called: "A Declaration of Dependence Upon the Soil and of the Right of Self-Maintenance." The high light of the conference centered in the discussion on the advisability of converting farm products into alcohol for admixture with motor gasoline.

D. L. M. CHRISTENSEN of Ames, Ia. submitted a report in which he contended that exhaustive tests with automobiles, trucks, buses, tractors and airplanes had proved that, as a blend with gasoline, alcohol was unexcelled. No change in present engine design had been necessary. A mixture of one gallon of the alcohol with ten of low-grade gasoline had given 8 per cent. better mileage and the same anti-knock rating as "regular" grades of gasoline, while a 20 per cent. blend had equaled in performance the best of premium fuels. In addition, the blend gave smoother and quieter engine operation, virtual elimination of gum and carbon, better acceleration, particularly at low speeds, and somewhat easier starting.

WILLIAM J. HALE of Washington, D. C., predicted that the use of alcohol for motor fuel might be the chemical means of stabilizing all agriculture. Different sections of the country would send different crops to its fermentation industries—in the South, the sweet potato; in the North, the potato and sugar beet; in the Middle Belt, corn, fruits and the Jerusalem artichoke, and everywhere waste wood, weeds and other undesired materials.

C.

A One and One-Half Volt Shave.—(*Chem. & Met.*, 42, 286.) A new type of electric razor recently was exhibited at the British Industries Fair. The Telerazor, as it is called, does not use an electric motor nor a moving blade, but a small vibrator in the handle of the razor operated by a 1½-volt battery, also in the handle, gives the nesessary oscillation of about 200 per second required for the shearing action which is claimed.

C.

The Use of Light for Plant Growth.—L. C. PORTER in the *General Electric Review*, Vol. 38, No. 6, reviews advances on this subject. Considerable fundamental research is being conducted on the effect of colors on the growth of plants. It is now known that blue light retards growth. It is believed that the reason that plants turn toward the light is not in an effort to obtain more light, but rather because the blue portion of the spectrum retards the growth on the side toward the light while the other side grows faster owing to the passing of growth hormones to the back side, thereby pushing the plants over toward the light.

In regard to the germination of seeds it has been found that lettuce seeds in water will germinate in a few hours under the influence of red light whereas under blue light it might take as many weeks.

A very interesting joint experiment is being conducted by the General Electric Co., the Boyce-Thompson Institute for Plant Research, and the Westchester Lighting Co. under supervision of Dr. J. M. Arthur in a specially constructed heat insulated greenhouse in which the only heat supplied is that from Mazda lamps. Plants in this greenhouse have come into blossom weeks earlier than those in an ordinary greenhouse and they are larger and more prolific. Provision is made for the supply of CO_2 to the plants by placing approximately 40 lb. of dry ice in a heat insulated box each week. A pipe, having small holes drilled in it at regular intervals, runs from this box along the bed and as the dry ice evaporates CO_2 is emitted through these holes.

The construction costs of a house of this type are lower, the heating costs compare favorably with those for the customary types heated with coal and maintenance is lower. Greenhouses of this type could be built several stories high.

R. H. O.

Out of Egypt—(**Wasps** U. S. D. A. Sheet No. 888).—In attempt to forestall widespread damage by the pink bollworm—the most destructive cotton pest in nearly all the important cotton-growing countries of the world—the U. S. Department of Agriculture has recently imported from Egypt three lots of promising little wasps. In the Department's insectary at Presidio, Texas, these insects are encouraged to multiply until a small army is created which then will be turned loose against cotton's enemy Number One. So far, the most difficult part of the task has been to bring the tiny immigrants safely to their destination. This was accomplished only by combining air express and fast ocean liners with modern refrigeration facilities. In this way, the insects made the trip from Cairo to Presidio in about two weeks.

A large number of American-born progeny to the variety *Micobracon kirkpatricki* are now ready for release in cotton fields. The other two newcomers—*Exeristes roborator* and Elasmus—are native parasites of the pink bollworm in Egypt. Some time ago Exeristes was brought into the United States from Europe to prey on the European corn borer. When liberated against the pink bollworm in Texas, however, this wasp seemed unable to adapt itself to conditions there. Entomologists hope the strain from the banks of the Nile will do better.

C.

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